CONSTRUCTION QUALITY CONTROL SYSTEM; A COMPARATIVE ANALYSIS.

Scott Holman Shepard

Construction Quality Control Systems;
A Comparative Analysis

by

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The three systems are highway construction statistical quality control, nuclear power plant construction quality assurance, and U.S. Navy contractor quality control. A comparative analysis of these systems and building construction quality control, which represents the traditional approach, is provided. Each approach to quality control is analyzed according to its planning, procedures, and organization and management aspects.

The comparative analysis provides an overview of construction quality control, and a set of management tools available to any owner contemplating a construction project.

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The Pennsylvania State University

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Construction Quality Control Systems:

A Comparative Analysis

A Thesis in

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Scott Holman Shepard

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ABSTRACT

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KEY WORDS

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LIST OF SYMBOLS

ACI	American Concrete Institute
A/E	Architect-Engineer
AEC	Atomic Energy Commission
AIA	American Institute of Architects
ANSI	American National Standards Institute
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASPR	Armed Services Procurement Regulation
ASTM	American Society for Testing Materials
CPM	Critical Path Method
CQC	Contractor Quality Control
ERS	End Result Specification
GAO	General Accounting Office
LCL	Lower Control Limit
NAVFAC	Naval Facilities Engineering Command
NRC	Nuclear Regulatory Commission
PSAR	Preliminary Safety Analysis Report
QA	Quality Assurance
QC	Quality Control
R	Range
SAR	Safety Analysis Report
SQC	Statistical Quality Control
UCL	Upper Control Limit
$\overline{X}$	Arithmetic Mean
10CFR50	Title 10, Atomic Energy Part 50, Licensing of Production and Utilization Facilities: Code of Federal Regulations

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CHAPTER I

INTRODUCTION

The construction industry has long prided itself on the excellence of its structures, yet quality control (QC) has traditionally been an afterthought. The emphasis has been placed on catching mistakes after they occur, rather than as they occur or before they occur. In recent years, attention to quality control has increased dramatically in certain areas of construction. Particularly noteworthy have been developments in highway, nuclear power plant, and U. S. Navy construction. The import of these developments is that QC should be a systematic effort pervading each phase of a project.

By contrast, the building construction industry has continued to emphasize traditional "after the fact" type quality control. This type relies heavily on the judgment and expertise of personnel involved. The more systematic approaches emphasize, to varying degrees, the importance of realistic specifications, effective organization and management, and effective procedures. The purpose of this thesis is to examine these developments by providing a comparative analysis of quality control methods in highway, nuclear power plant, Navy, and building construction. The analysis will lead to the conclusion that the building industry can benefit from experience in other areas by adopting some of their approaches to quality control.

The Need for Quality Control

Webster's dictionary defines quality control as "a system for maintaining desired standards in production or in a product, especially by inspecting samples of the product." In consumer product industries, the need for maintaining standards is fundamental and obvious. If a company's products are of unsatisfactory quality, the public won't buy them. In construction, the need is not so obvious, because the contractor (producer) is not in business to please the public, but to please the owner, and the owner may or may not have the public interest foremost in mind.

To best understand the need for QC in construction, it must be examined from the viewpoints of the owner, contractor, and public. From the public point of view, a structure must be safe and serviceable, and there is no doubt that attention to standards of quality during construction are contributory. The need of a contractor is quite different. From his point of view, quality control means ensuring that the requirements of the plans and specifications are met. If they are, his need is satisfied, and he is paid for the work. The owner's need is pivotal. He must ensure that the structure is safe and serviceable, and he must ensure that the contractor complies with the plans and specifications.

Highway, nuclear power plant, and Navy QC programs have recognized, to varying degrees, that the need for safety and serviceability, on the one hand, and compliance with plans and specifications, on the other, are interdependent. Building construction and traditional approaches often treat the two needs as independent, a situation which may cause conflicts of interest. Succeeding chapters will show how systematic programs meet owners' and contractors' needs through

specifications, organization and management, and procedures; and how traditional programs meet the needs through the skill, experience, and intuitive management of personnel.

The Advent of Quality Control Systems

Highway, nuclear, and Navy QC systems differ from building programs in that they represent a more systematic and comprehensive approach. They also differ because the development of each was influenced significantly by the federal government. It is instructive to understand the conditions under which each system developed and why they are referred to as "systems." It is also important to understand the development of traditional QC.

It is recalled that the dictionary definition of quality control is a "system for maintaining standards. . ." This being the case, it would seem redundant to refer to a quality control "system;" however, a number of authors (1, 22, 38) have described a "systems approach" to QC as an integrated effort which considers all phases of a project, not separately, but as a whole. In a sense, traditional approaches have failed to live up to the dictionary definition by not being "systematic" enough. Thus, it has been necessary to reemphasize the term in the newer approaches.

Traditional quality control implies a division of responsibilities in the construction process. The designer or architect-engineer (A/E) is responsible for writing specifications but is not tasked with carrying them out. The contractor is responsible for performing the work but is not tasked with controlling the quality. The owner must initiate a control and acceptance program and may assign the responsibilities to the A/E, his own forces, or an outside agent. Traditional

control also implies a discontinuity between the functions of specification and control. The specifications describe what is to be constructed and how it is to be done, but they do not establish guidelines for inspection and quality control. The inspector must be as skilled in interpreting contract requirements as the designer is skilled in writing them.

Two points about traditional QC must be emphasized. First, its use is not restricted to building construction; and second, under the right conditions, it can be very effective. Traditional methods have been prevalent, and still are to some extent, in all four areas. The key difference is that while the highway, nuclear, and Navy areas have recognized the need for change, the building area has not. The comparative analysis will show how, why, and to what extent each area has recognized the need for and has implemented change. It will identify possibilities for change in building construction, despite the fact that traditional approaches have achieved success.

The three newer QC systems were influenced by the federal government for different reasons and to varying extents. Highway construction programs were developed as testing revealed that statistical rather than intuitive methods would be necessary to properly prepare and then enforce specifications. The impetus for change occurred during the 1960's as the federally funded interstate highway system was developed. In this case, the federal government indirectly influenced changes as the state governments conducted studies and implemented modifications. Nuclear construction programs were a direct result of federal laws which mandated safety requirements for the design, construction, and operation of power plants. The laws were

implemented by the Nuclear Regulatory Commission (NRC) through regulations which require that plant owners establish quality control programs with specified features. The Navy Contractor Quality Control (CQC) program was initiated when the Department of Defense determined that contractors should assume a greater role in control of quality.

The systems differ not only in the extent of government influence, but also in the areas of QC emphasized. As stated earlier, the significant areas of development have been specifications, organization and management, and procedures. Highway programs have emphasized each of these areas through a statistical approach to specifications, control, and acceptance; and reassignment of responsibilities (organization). Nuclear programs have placed most emphasis on the role of effective organization and management in assuring that QC goals are met and accounted for at all stages of a project. The Navy has emphasized the proper assignment of responsibilities (organization and management) during the construction phase. The analysis of each system, including building construction, will provide details as to how its objectives are met. The comparison will serve to identify their strengths and weaknesses. In the aggregate, the thesis will portray four very different approaches to QC, each having the same immediate problem, yet motivated by different forces; each at a certain stage of development, yet capable of improvement.

A Comparison of Highway, Nuclear, Navy, and Building Construction

The differences between highways, nuclear power plants, and buildings are visually and functionally obvious. The differences between the construction of each, however, should be identified. Navy

construction is mostly related to buildings; however, it encompasses road building and other forms of heavy construction as well. To facilitate comparison, the term "building construction," in this thesis, shall exclude construction in the Navy or federal government. Highway construction has been referred to as linear construction in that it follows a path and because its work items are repetitive. The processes of earthmoving, grading, compacting, and paving are accomplished over and over again as the project proceeds. Highway pavements are classified as rigid (portland cement concrete), or flexible (bituminous or asphaltic concrete). A sizeable project involves the production of massive quantities of paving materials over a long period of time. A highway project, due to its linear nature, involves relatively few trades.

Building construction is essentially nonlinear. Although many of the work items are repetitive, they do not span the entire project, as in the case of highways. In a building project, the earthmoving operations are completed at one time and occupy only a small percentage of the contract time. By contrast, the earthmoving operations in a highway project are completed gradually as the project advances and occupy a large percentage of the contract time. Buildings are classified as structural steel or reinforced concrete. Depending on the size and type of structure, a building may require large quantities of structural materials, such as concrete, over a significant length of time. In such a case, the production of concrete may be similar to highway production, while placement is quite different. The major difference is that concrete in buildings often involves varying shapes placed at varying elevations, while highway pavements are uniform in

shape and elevation. A building project involves a large number of trades.

Nuclear power plant construction shares many of the characteristics of building and highway construction. It is nonlinear in that it occupies one site and completes its major work items, such as sitework and structural work, in sequence. It is similar to highway construction in that massive quantities of materials, requiring large equipment fleets, are involved. The significant differences between nuclear and conventional construction are time, cost, and sophistication. While conventional (highway and building) projects are typically completed in under five years, a nuclear project typically spans ten years. Conventional project costs are measured in millions of dollars, while a nuclear plant may total $1.5 billion. Nuclear projects involve levels of sophistication in construction methods and installed equipment that are unheard of in highway, Navy, or building construction. These aspects have a direct impact on quality control and will be discussed later in the text.

Although there are significant differences in magnitude, sequencing, difficulty, and variety of work involved in the various areas, there are several common denominators which provide the foundation for a comparative analysis of QC systems.

The first common denominator is contract administration. Each type of construction is performed under one or several construction contracts between an owner or owner's representative, and a constructor, commonly a general contractor. Each type involves relationships (formal or informal) between three parties: the owner, the designer or A/E, and the contractor. Numerous other contract administration terms,

such as pre-bid conference, pre-construction conference, shop drawing, change order, field change order, final inspection, punch list are common to each type of construction. The significance of these similarities is that the commonality of nomenclature and interpretation thereof (despite the huge differences between the structures) link their erection inexorably into the same business: construction.

Another common denominator is project management, which is the art or science of ensuring the success of a project through management techniques. The techniques are practiced by owners, A/E's, and contractors for their own best interests. Cost accounting, scheduling, procurement, coordination of subcontractors, labor relations, and public relations are all aspects of project management, and are therefore common to each type of construction. There is some controversy in the industry as to whether or not quality control is a project management function. The fact that many of its tasks relate to cost and schedule control is seen by many as a conflict of interest. This subject will be discussed in detail under the organizational aspects of each QC system.

Further common denominators are certain construction materials and work items. These include numerous civil, structural, architectural, mechanical, and electrical components, such as select fill, reinforced concrete, interior finishes, drain pipes, and electrical conduit, respectively. One material, reinforced concrete, is widely used in each area. In addition, its QC has received considerable attention by researchers, professional societies, and specification writers.

In addition to mutual problems in contract administration, project management, and materials, the areas of construction also share concerns in quality control, which may be expressed interrogatively. What do we want? How do we get it? How do we ensure that we are getting what we want? Did we get what we wanted? These questions reflect problems which have been dealt with uniquely by various segments of the industry. Such matters as contractor plans for quality control, qualifications of inspectors, documentation of inspection and testing, procedures for sampling and testing, quality assurance, and acceptance are familiar to managers in each area. The comparative analysis will explore the similarities and differences in the handling of these areas as they apply to specifications, organization and management, and procedures.

The Need for Research

While there have been significant advancements in construction quality control, the development is by no means complete. State highway agencies have only begun to implement new programs, and for only selected materials. There is widespread belief that nuclear programs are overregulated and overrestricted. Navy programs have undergone a number of revisions to attain maximum efficiency without unduly burdening contractors. Although the federal government has influenced QC development, the recommendations for change have come from separate departments. The industry is fragmented, and it is this condition which has permitted significant advancements in some areas with little or no advancements in others.

Under the premise that there is a need for continued improvement of programs within each segment of the industry, an important aid to such development is the knowledge of experience and progress over several industry areas.

The trend in control of quality is away from the traditional, intuitive approaches toward the more organized and scientific approaches. The comparative analysis of QC systems provides the manager of a traditional or semideveloped program with the background information that he needs to create his own system. Without this information, he may repeat the mistakes of others, or worse, may be ignorant of an available tool or concept.

Objectives and Scope

The objective of this thesis is to provide a single document which summarizes the management aspects of several existing quality control systems, and which, through a comparative analysis, provides a generic overview of construction quality control. The result is a collection of tools from which an owner or construction manager can draw to meet his quality goals.

The study includes four programs represented by highway, nuclear power plant, U. S. Navy, and general building construction. The programs are compared on the basis of planning for quality (specifications), and implementing control (organization and management, and procedures). The analysis demonstrates the potential of newer approaches to QC by proposing their applicability to traditional approaches represented by building construction.

It should be noted that the analysis is primarily concerned with the state of the art of quality control management. An equally important topic, the state of the art of construction quality, is not within the scope of the thesis. Thus, for example, the improvement in the manageability of highway construction quality control, due to the introduction of statistical quality control, will be discussed. The question of whether or not SQC has improved the quality of highways is not within the scope of the thesis.

CHAPTER II

HIGHWAY CONSTRUCTION QUALITY CONTROL

The construction of highways in the United States is accomplished with public funds under the supervision of state highway agencies. The agencies are charged with completing highways of good quality within budgetary and time constraints. Although the agencies may accomplish minor construction or maintenance tasks with their own forces, they rely on private contractors to accomplish most projects.

Highway contractors are selected on the basis of competitive unit price bidding, and construction contracts are awarded to the low bidder at a fixed price with a stipulated completion date. As with other types of construction, the highway construction contract includes documents (plans and specifications) which define the work in detail. It is through effective administration of the contract documents that the agencies control the costs, completion times, and quality of the highways.

The starting points for cost and schedule control are, of course, the fixed price and the contract completion date. The starting point for quality control, not so easily defined, is the specifications. During construction, each item of work is monitored and controlled to the extent that actual conditions will allow. Often unforeseen circumstances necessitate modifications to the contract documents. When the job is completed, the agency's success in controlling cost and time can be immediately evaluated in terms of actual costs and the actual completion date. Under traditional QC systems, the success of the quality

control effort is not so readily apparent and, in fact, is viewed more as prerequisite to final completion than as a measurable result.

In practice, the quality of construction is monitored or measured on a daily basis, and satisfactory quality is a basis for periodic payments to the contractor. In traditional systems, the determination of quality is a subjective evaluation of an inspector as to whether or not items of work conform to the specifications. In recent years, experts have questioned the entire quality control process, including the specifications. They have proposed, and many states have accepted, the adoption of statistical quality control procedures which replace many of the intuitive judgments of the past with scientific bases for decisions.

This chapter discusses the reasons for the shift to statistical quality control (SQC), explains the operation of an SQC system, and explains the impact of SQC on QC planning, procedures, and organization and management.

Background

The traditional techniques of quality control in highway construction are more of an art than a science. This implies that the enforcement of specifications can be inconsistent and depends to a large degree on the skills and attitudes of individual inspectors. This condition is fostered by specifications and assignment of responsibilities.

Traditional highway specifications have been described as more closely resembling recipes than specifications (32). This is because they tell the contractor what to do and how to do it, more than

telling him what the result should be. When quality is defined, it reflects the experience and judgment of the designer rather than the true needs and capabilities of the construction process or of the available materials (32).

It would appear that a recipe type specification would be easy to enforce by accepting all work that follows the recipe and rejecting work that doesn't. In practice, however, actual jobsite conditions or mitigating circumstances may cause deviations from the specification. When this occurs, it may be in the best interests of the state to accept the deficient work, but because the specifications do not provide guidance in such matters, the inspector or engineer must exercise his own judgment. For example, the typical specification for concrete strength may state the following: "The minimum compressive strength at 28 days shall be 3000 psi (2)." If the actual test results indicate that 2900 psi has been obtained, the engineer must decide whether to accept the lower quality work or require that it be removed or replaced. Realizing that the latter option would be inconvenient for all concerned, he recalls from experience that 2900 psi concrete will provide satisfactory service and decides to accept the work. It is significant that traditional specifications do not normally make specific allowance for such decisions, but instead give the engineer general authority to interpret the contract.

From the above, it is clear that project quality decisions are not totally intuitive, but are based in part on sampling and testing of materials. In a traditional quality control program, "representative" samples of materials are taken periodically throughout the job. A representative sample is a small portion of material which is

expected to "represent" all of the material or an indicated amount of the material. The inspector is generally tasked with taking samples which appear to best represent the whole. Representative samples are tested or measured, and the results are assumed to indicate the quality characteristics of the whole. Although the test results may be conclusive, considerable judgment on the part of the inspector is required in the sampling process itself. That is, the inspector may be biased in selecting a sample from a "bad looking" portion or a "good looking" portion.

The recipe nature of specifications, the lack of specificity on how to handle deviations in specifications, and the flexible sampling and testing procedures all place a heavy burden on the inspector's judgment, and result in inconsistent enforcement of specifications in a traditional quality control system.

Another aspect of QC is the assignment of responsibilities. In a traditional system, both the day-to-day measuring, testing and control of the construction process, and the less frequent inspection and acceptance of work in place are the responsibility of the state highway agency. Obviously, when the same organization controls the work and then later inspects it for acceptance or rejection, there are numerous opportunities for conflict of interest. For example, during a concrete operation, a state inspector may order the contractor to add water to an unusually stiff mixture. If later a test cylinder indicates a low strength, then because of the inspector's "control" over the addition of water, it would be difficult for the state to reject the concrete. In a reverse situation, an inspector who fails to exercise control, for example, by allowing a contractor to place an

excessively wet batch of concrete, may place the state in the same situation if the test strength is low.

It is often stressed that when the contractors and state agencies work cooperatively, the above "traditional" procedures result in perfectly satisfactory highways (32). It is important, therefore, to establish the reasons why SQC has emerged as a revolutionary concept in highway construction.

The Need for Change

The first indicator of a need to study and modify existing quality control concepts was the AASHO Road Test of 1959 (13, 51). The road test was an experiment to determine the extent to which standard highway specifications could be met under the most ideal conditions. An eight mile long highway was constructed under tightly controlled conditions with a well-staffed, competent inspection force, on site laboratory facilities, and a highly qualified contractor. The contractor's performance not only was tightly controlled, but was monitored and measured far more frequently and stringently than under conventional procedures. Sophisticated and rapid testing methods allowed engineers to correct processes as the work progressed.

The results of the road test were astounding! Despite the heavy emphasis on quality control, the attempts to meet standard highway specifications were largely unsuccessful. In the words of one participant, ". . . we were unable to meet the specifications for many of the construction items within a country mile (13)."

The study concluded that the significance of specification requirements was not understood, and that traditional sampling plans

were inadequate (13). The fact was that engineers based requirements and tolerances on experience and achievable variations. The study uncovered a lack of knowledge of what was achievable under conventional practices (51), and of the effects of variation on performance. In short, the specifications were not being met and the sampling and testing procedures were not adequately measuring what values were being met.

Another important conclusion was that "failure to meet specifications all the time was no indication that the product would fail to perform as intended or that it would not last as long as expected (51)." In other words, the vast majority of highways constructed under conventional specifications were performing quite satisfactorily, and it would be unfair to penalize contractors for variations in quality which did not impair performance.

The AASHO Road Test established scientifically that there was a need for changes in highway quality control in planning and procedures. The planning would involve the development of realistic specifications, and the procedures would involve equitable sampling and testing.

Extensive investigation and research in the early 1960's reinforced the findings of the road test. It was determined that there should be a system in which the design specifies what is needed, but can and should be modified according to the quality and performance that is actually achieved (26). In essence, the need was for an interrelationship or interdependence between design and quality control.

Additional needs for change became apparent as the interstate highway program increased the tempo of operations. Traditional

control procedures were criticized because they were economically inefficient, placing too much emphasis on "inspecting quality into a job." Conventional sampling and testing procedures could not keep pace with newer, more rapid construction methods (11).

In the late 1960's, a consensus among researchers, state agencies and the federal government emerged that the answer to highway quality needs was statistical quality control (SQC). The government, on the basis of its funding of interstate highway projects, exerted considerable pressure on state highway agencies to adopt SQC programs, and by 1976, 33 states had adopted or had plans to adopt statistical methods (50).

Statistical Quality Control Concepts

Statistical quality control is a discipline which has seen extensive employment in the manufacturing industry, where it considers all quality matters from the point of view of specification, production, and inspection. In this perspective, it is viewed as "a kit of tools which may influence decisions related to the functions of specification, production, or inspection (13)." A key factor is that cooperation among those responsible for each function is a prerequisite to SQC effectiveness.

In construction, specification, production, and inspection become specifications, process control, and acceptance. Specifications represent the planning or design phase of a project, during which desired quality levels are established. As mentioned earlier, these levels are based in part on test data of performance levels actually achieved in earlier projects. During the construction phase, process

control techniques are employed to achieve quality levels through active control procedures. In SQC, the contractor is directly responsible for this control, and employs SQC techniques to that end. It is often said that in highway construction, the contractor is responsible for quality control, and in this usage, quality control and process control are synonymous. Acceptance is the phase in which the highway agency determines whether or not the contractor's work conforms to the specifications. The statistical techniques employed in this regard are called acceptance sampling and testing.

The detailed mathematics of SQC, including the probability and statistics concepts employed, have been treated in detail in a number of references. Particularly, comprehensive treatments can be found in Statistical Quality Control, by Grant and Leavenworth (24), and Statistical Quality Control of Highway Construction, by Willenbrock (51). The intent of this discussion is to provide an overview of what SQC can do. For an explanation of how it works, the above references are recommended.

The key advantage of SQC has been described as its capability of expressing numerically, engineering judgment and substantial compliance (21). A continuing problem with traditional specifications has been the use of such phrases as "substantial compliance" and "reasonable close conformity," which require the field engineer or inspector to make their own judgments based on experience and intuitive reasoning. SQC eliminates much of this problem by providing numerical target values and tolerances. Stated another way, statistical concepts contribute to better communications between the various parties to a contract by permitting more explicit instructions

to be specified. Improved communications was the basis for the Bureau of Public Roads' recommendation that statistical methods be incorporated in highway construction specifications (32).

Another advantage is that statistical methods recognize variability in construction. The concept of variability simply means that no process, be it manufacturing or construction, is perfect. There will always be some variation in quality, large or small, due to a variety of factors including the features of the process and the material characteristics. Traditional specifications have ignored this law of nature by setting fixed values as requirements, such as a concrete strength criterion, mentioned earlier, which states, "the compressive strength of concrete shall be a minimum of 3000 psi at 28 days." Other specifications have included allowable variations based on judgment or experience. Statistical specifications provide target quality levels and statistically derived tolerances. The tolerances establish upper and lower limits, sometimes referred to as specification bands. The band limits are spaced far enough from the target value that normal construction, sampling, and testing variances are taken into account, and all test results are expected to be within specifications when the average value is close to the target value or center of the band (39).

A further advantage of SQC is that responsibilities for process control and acceptance are divided between the contractor and state highway agency, respectively. This permits the contractor a greater degree of flexibility in choosing construction methods and possibly results in lower costs. The state is relieved of the responsibility

for controlling the contractor's operations and the tentative position of having to inspect the same work it controlled is eliminated.

A number of statistical methods may be thought of as tools with which an owner can selectively pattern his own SQC program. Particularly significant tools are control charts, sampling plans, decision tools, and incentive/penalty payment plans. Control charts are process control devices which present test results graphically in relation to target quality levels and tolerances. Their chief advantage is that they provide frequent visual indications of quality levels achieved, which facilitate early corrective actions should the process develop problems. The details of process control and its employment of control chart techniques will be discussed later in the chapter.

Sampling is the procedure by which a small portion of a larger quantity is removed and tested to determine if the larger quantity is or is not acceptable. This is contrasted to 100% inspection in which all portions of the quantity are tested. The advantages of sampling are that it is less time consuming, easier to perform, and therefore less expensive. The advantage of 100% inspection is that it provides greater assurance of quality if that quality is suspect. In highway construction, the practicality of sampling has made it the rule for the control and acceptance of materials requiring testing or inspection other than a simple visual check.

Because both traditional and newer QC programs rely on sampling, it is necessary to differentiate between their approaches to it. Conventional sampling is based on the concept that a single sample represents the whole, and that the inspector must decide where and how often to take samples. The process is often termed "biased" sampling,

because the inspector may be influenced by the appearance or otherwise impelled to sample a portion of the whole which does not accurately indicate the characteristics of the whole. The philosophy of this approach is that if any portion, regardless how small, of the whole fails to meet the specifications, then the whole should be rejected. The danger of this approach is that it does not recognize the law of variability. Consequently, there is no way to consider the possibility of rejecting a quantity of work that will perform satisfactorily in service, or of accepting a quantity of work that is unacceptable for service.

Statistical sampling employs the concept of "random" sampling, which eliminates bias by ensuring that all portions of a quantity, called a "Lot," have an equal chance of being selected. Statistical theory has confirmed that the use of random samples enhances effective control and acceptance by facilitating probabilistic predictions of quality levels. In SQC, rules of sampling dictate how, where, and the number of samples that are to be taken and under what circumstances a Lot or a portion thereof (called a Sublot) may be accepted or rejected. These rules are agreed to prior to commencement of construction by inclusion in the specifications, and are known as sampling plans or acceptance sampling plans.

An often emphasized point about sampling and acceptance is that its purpose is not to control quality, but to determine courses of action (21). In other words, it provides information with which decisions to accept or reject can be made. To further aid in this decision making, certain statistical techniques or decision tools are available. These involve the consideration of criticality of the

item of work or material to be tested, and consideration of the risk of making an incorrect decision.

Central to acceptance decision making is the theory of risks. In both conventional and statistical sampling, there is a possibility or risk of accepting an unsatisfactory lot or quanitity of material or work or of rejecting a satisfactory quantity. The first case is known as the "buyer's risk," and the second, the "seller's risk." The theory of risks allows the agency to determine what risks it is willing to accept, and then adjust the frequency of testing or precision of tests to ensure that the risk objectives are met.

An aid to determining acceptable risks is the categorizing of work items or materials according to the criticality of defects. Four classes of defects commonly used are "critical," meaning the material or structure is dangerous to use; "major," a condition whereby the material or structure is unusable or its performance seriously impaired; "minor," implying impaired performance, but not severely; and "contractural," meaning no effect on performance. When portions of the work are so classified, appropriate risks can be assigned, and sampling plans can be developed.

The decisions discussed thus far are all made before work commences. Despite allowance for criticality of work and risk, and carefully devised acceptance sampling problems, however, the dilemma of how to handle nonconforming work, whose removal and replacement is not in the best interests of the state, persists. In conventional QC programs, the inspector or resident engineer must exercise judgment and intuitive reasoning to determine whether or not the work "substantially complies" or is in "reasonable close conformity" with

the specifications. In an SQC system, the specifications provide what is known as a reduced payment plan. Under this concept, a predetermined formula is used to reduce the price of defective lots which are to remain in place. It should be noted that application of such a formula is an option of the engineer, who retains the right to reject the work, and the contractor, who retains the right to remove and replace the work for full payment.

The concepts of statistical quality control are not limited to the advantages and tools in the above discussion; however, a familiarity with them will serve as a basis for a more detailed discussion of highway quality programs. As mentioned earlier, the programs shall be analyzed in terms of their planning, organizational and management, and procedural characteristics. It shall be seen that the planning phase involves the development of "statistical end result specifications;" the organizational and management aspects involve the division of responsibilities; and the procedural aspects include process control, acceptance, and assurance.

Quality Control Planning

Quality control planning generally involves the establishment of standards followed by translation of these standards into specifications. As explained earlier, traditional plans have relied upon recipe type specifications, while SQC systems use statistical end result specifications (ERS). The key difference is that the state highway agency performs many control functions in the first case, while the contractor performs all process control under the second. In both cases, the state

performs the acceptance inspections, and the role of acceptance is, if anything, heightened by the ERS.

The modifier "end result" can imply that the state performs no inspection until a work item is complete, creating a situation in which defective work is not discovered until a work item is complete, and therefore difficult or inconvenient to remove and replace. Recognition of this implication has led Willenbrock (51) to define a third type of specification, the "Quality Assurance Specification," which is statistically based and requires contractor process control, but which allows for day-to-day agency inspection (not control) of the process. The Transportation Research Board defines a statistically oriented end result specification as one where "instead of inspecting the process that produces a certain material or item of construction, the agency monitors the contractor's control of the process and accepts or rejects the end product (50)." In this discussion, the use of the term "end result specification" shall imply that agency monitoring of the contractor's process control is both permissible and desirable. A point frequently stressed is that the day-to-day activity of the agency, whether it be called inspection or monitoring, should not be interpreted as an opportunity to tell the contractor what to do. It should be thought of as a spot check, wherein an inspector may merely point out that something is wrong; the contractor must decide what to do about it.

The purpose of a statistical specification is twofold: to present the design and to describe the inspection (24). A highway specification accomplishes this by setting quality levels and providing control procedures and acceptance plans. The specifications are based

on statistical principles which have been listed by the Federal Highway Administration (21) and are summarized below:

1. Sampling methods are more practical than 100% inspection.
2. Variations, both real and apparent (due to sampling and testing errors) exist, and therefore samples may or may not adequately represent the total process.
3. Statistical techniques, including random sampling, can predict probabilities that actual material or process quality levels are within tolerance, recognizing that outliers (portions of work better or worse than tolerance limits) may be missed in the sampling process.
4. Specifications, recognizing variabilities, should be written on a probabilistic basis to ensure that unavoidable variations are not confused with poor workmanship.
5. Consideration for the high costs of producing and controlling highly uniform products vs. the lower costs with satisfactory performance, yet possibly higher maintenance costs, of producing less perfect materials is necessary when setting quality levels.
6. Both buyer and seller must understand the rules for sampling and accepting work.
7. The specifications should be written so as to minimize the buyer's and seller's risks of accepting poor quality work or rejecting good quality work, respectively.

A statistical highway specification contains five key elements: quality levels, responsibility assignments, process control guidelines, acceptance plans, and reduced payment plans. The most important element

is the description of levels of quality accepted. For this reason, a great deal of research has gone into the question of how best to establish levels and tolerances, and importantly, which material or process characteristics to measure.

Beaton (11) has pointed out that not all construction items need be controlled statistically, and industry employment of SQC has borne out his hypothesis. The most widespread applications of statistical methods have been in the construction of bituminous pavements. Portland cement concrete pavements and structural concrete programs are used to a much more limited extent. SQC of soil compaction is envisioned as an area of potential application by industry leaders, although no programs are presently in effect.

Once a material, such as Portland cement concrete, is selected for statistical quality control, engineers and researchers must decide which of its characteristics govern performance, and therefore need to be sampled and tested. For concrete, the usual properties measured are compressive strength, air content, slump, unit weight, aggregate gradation, and thickness of pavement.

When a decision has been made to develop a specification, a state agency must invest 1½ to 3 years in a testing program which provides statistical data on each of the material properties selected. The testing is generally performed on materials produced under standard specifications so that the data can be analyzed to determine sources of variance. This variance analysis may then become the basis for the establishment of tolerances.

It should be pointed out that not all writers are in agreement as to the role of statistics and variance analysis in the establishment

of quality levels and tolerances. Mather has written that SQC is indispensable to proper production, inspection, and specification compliance and enforcement, but "can do nothing, directly, to make more appropriate the levels of quality performance required by specifications nor can it improve the procedures by which quality levels and hence specification limits are selected (31)." A report prepared for the Federal Highway Administration entitled Quality Assurance for Portland Cement Concrete states that the setting of specification limits is strictly an engineering function, and that the limits once established should not be adjusted to fit statistical variances, but only to conform to actual performance (18).

The alternate point of view holds that statistics is a valuable tool in setting limits. In manufacturing SQC, a designer must not only consider the service needs of the product, but also (1) the capabilities of the production process to produce to given specification limits, and (2) the means used to establish compliance (24). These principles have been applied in practice by state highway agencies. The means used to establish compliance are the process control requirements and acceptance plans. The capabilities of the production process are determined through variance analysis.

Variability, thus far, has been explained as the difference between actual measurements and target quality levels. There are a number of variability components, however, which should be considered. Willenbrock (51) has listed four components of overall variation. The first, "inherent variation" is described as the random variation of a material due to the nature of its properties. "Sampling and testing variation" represents changes that occur during the sampling or testing

process due to operator error, lack of precision in measuring, equipment difficulties, testing procedure, etc. "Within batch variation" is due to differences in properties between samples of the same batch, such as the difference in concrete slump from the front of a load to the back. Finally, "batch-to-batch variation" represents differences in test results between batches due to ineffective process control.

While the purpose of SQC is not to eliminate all variations, it is the goal of a variance analysis to identify and reduce the nonrandom sampling and testing, within batch, and batch-to-batch errors. The identification is important in determining the source (contractor, agency, testing lab, etc.) of variation difficulties. The reduction of nonrandom variations facilitates the setting of acceptance limits by defining normal variation, which is both realistic and enforceable.

To summarize, the setting of quality limits using statistical methods involves the exercise of engineering judgment in setting target levels of quality; a sampling and testing program to establish variabilities; a variance analysis to define normal variances and to isolate unnecessary variances; and the setting of realistic tolerances based on the variance analysis. The alternate method involves the collection of data and variance analysis for purposes of comparing overall variance to quality limits established through engineering judgment alone. If the overall variance exceeds the engineered limits, then an attempt to reduce it through process control or screening is made (18). While the second method is a cautious, conservative approach to SQC, the first method appears to be the preferred industry approach.

The setting of quality levels and tolerances is the most important aspect in the development of specifications because the target levels

establish the performance and life of the pavement or structure. The remaining aspects are involved with ensuring that the targets are attained.

The assignment of responsibilities of process control to the contractor and acceptance sampling and testing to the agency or owner is fundamental to any SQC system, and therefore must be carefully stated in the specifications. Typically, the general paragraphs define the division of responsibility and outline the responsibilities of the state and the contractor. While the textbook definition of SQC requires a sharp delineation between process control and acceptance, it should be recognized that there is a great deal of reluctance on the part of field professionals to give up their control. As a result, specifications differ in the control responsibilities retained by the state inspector or engineer. For example, the Transportation Research Board reports that a number of states employ statistical methods, such as random sampling, yet continue to provide their own process control services (50). The Pennsylvania Department of Transportation (Penn DOT) Form 408 specifications make the contractor responsible for the quality of construction and materials, yet continue to give the engineer broad authority to "determine the limits of reasonably close conformity," and to suspend work "due to the failure on the part of the contractor to carry out orders given . . . (40)." Louisiana's end result specifications provide a sharp separation between contractor and state responsibilities by specifically stating that inspectors may not by act or word assume responsibility for process control testing (3).

The process control portion of a specification requires that the contractor maintain his own quality control system for the purpose of

ensuring that materials and work conform to the specifications. The system requirements are set forth in general terms and include such items as documenting inspections and tests, providing charts and records to the state upon completion, prompt correcting of process or equipment errors, and providing properly calibrated measuring and testing devices. The contractor is often required to submit a written process control plan for approval or to subscribe to a suggested plan provided by the state. The details of a contractor plan will be developed in a subsequent discussion of process control procedures.

The acceptance portion of a specification provides the guidelines or rules under which work is accepted, rejected, or accepted at a reduced price. Included are criteria for lot size, sample size, location of sample, test method, acceptance location, and procedure for acceptance determination. Also included are limits of acceptance and acceptance plans. The limits of acceptance, not to be confused with quality levels, specify the percentage of a material or work item which must be within specified tolerances (51). The acceptance plan sets forth the necessary statistical tables and formulas to compute these limits.

The reduced payment provisions generally accompany the acceptance criteria and are merely tables which indicate percentages of full payment to be made vs. the amount that measurements are out of tolerance. An important concept of reduced payment plans is that resampling and retesting of nonconforming lots to verify that they are out of tolerance is not permitted in a statistical acceptance specification. The reason for this departure from tradition is that resampling introduces bias and defeats the intent of random sampling as a means to predict the actual

quality level of Lots. It is no more acceptable to retest nonconforming work than it would be to recheck conforming work.

The fully developed statistical end result specification is an indispensable tool in the pursuit of quality highways. It provides a more rational basis for state inspection and monitoring of progress and a more equitable system for contractors. A good specification, however, is only of value if properly executed, and proper execution requires effective procedures carried out in a well-managed, organized fashion. The remainder of this chapter will be devoted to these aspects of highway construction quality control.

Quality Control Procedures

Quality control procedures are the methods and techniques that highway agencies and contractors use in carrying out their programs. These procedures may be stated in the specifications, or may be self-generated for their individual needs. In conformity with the division of responsibilities, process control procedures and acceptance procedures will be discussed individually. Also described will be the concept of quality assurance procedures which states may use to evaluate control and acceptance programs.

Process Control. The philosophy of process control has been summed up in the popular clichés, "an ounce of prevention is worth a pound of cure," and "you can't inspect quality into a project." The idea is that the best acceptance program, and the most highly qualified inspectors cannot save an improperly controlled job. The aim of process control as mentioned earlier is to catch mistakes as, or before they occur, not after they occur.

To properly implement process control procedures, a contractor must prepare a plan, develop control techniques, and document all events.

A process control plan is similar to the specification requirements for process control in that it provides generalized statements of what the contractor's responsibilities are, and how he will carry them out. As stated earlier, a contractor may, at his option, elect to adopt the provisions of a state's suggested plan in lieu of writing his own. Penn DOT's "Suggested Guidelines for Contractor's Quality Control System" have been reprinted in Reference (51) and include the following highlights:

1. A statement that the contractor must perform, or have performed, the inspection and tests necessary to substantiate product conformance.
2. A requirement that the contractor maintain adequate records of all inspections and tests, and that his documentation procedures are subject to approval of the state.
3. A requirement that prompt corrective action be taken if nonconforming work is discovered.
4. A requirement that random sampling procedures, as outlined in the specifications, be employed in all process control sampling.
5. Allowance for alternative sampling and/or testing methods if approved by the state.

6. Provisions for contractor control of nonconforming materials to include identification, isolation, and disposition.
7. A statement of the state's rights to inspect materials not produced by the contractor with the understanding that process inspection by the state does not constitute final acceptance of the work.
8. A list of specific measurements and tests for materials, such as bituminous concrete, or Portland cement concrete.

The chief process control technique or device is the control chart, which is a graphical display of measurements or test results. This mode provides an easy way to visually compare test data to specification values, and to study variations. The contractor is then able to determine whether the process is "in control" or "out of control" on a day-to-day basis.

As discussed earlier, a variance analysis isolates values for inherent, sampling and testing, within batch, and batch-to-batch variation. In a parallel fashion, control charts provide a type of variance analysis by assigning causes of variation in the determination of whether or not the process is in control. In control chart analysis, inherent variation is termed a "chance cause," while the other forms of variation are called "assignable causes." The objective of process control is to discover and minimize assignable causes of variation.

Willenbrock (51) has listed nine benefits of control charts:

1. Early detection of trouble before rejections occur.
2. Decrease in product variability.
3. Establishment of process capabilities.

4. Capability of saving penalty and rework costs.
5. Decrease in the frequency of inspection for processes in control at a satisfactory level.
6. Provision of a rational basis for establishing or altering specification requirements.
7. Permanent record of quality.
8. Basis for acceptance of a product by a purchaser.
9. Instillment of a sense of "quality awareness" in an organization.

There are a number of control chart applications available depending on the nature of the material properties, how they are to be accepted, and the statistics that will be selected to represent them. The most widely used charts in highway construction are called "control charts for variables" because the data represented are actual measured properties, such as compressive strength, air content, etc. Less frequently used in highways, but popular in manufacturing industries, are "control charts for attributes" which consider inspections or tests as "conforming" or "not conforming," and represent the data as "percent conforming." An example could involve the visual inspection of concrete blocks, where cracked blocks are not conforming and crack-free blocks are conforming.

In highway concrete construction, the commonly used control charts for variables are $\overline{X}$ (spoken "bar X") and R charts. These provide graphical displays of sample "means" and "ranges," respectively. Although a sample usually consists of a number of separate measurements, it is convenient to describe its level of quality and variability by single numbers. The sample mean is defined as the arithmetic average

of the individual measurements and is an indication of the sample's quality level. The range is defined as the numerical difference between the highest and lowest measurements, and is an indication of variability. Both charts are necessary because it is possible to have a set of values which produce an acceptable mean, but an unacceptable range, or vice versa.

Examples of concrete properties adaptable to control chart analysis are slump, air content, strength, amount of cement, and amount of water (18). Possible soil compaction properties include moisture content, wet density, and relative compaction. Figure 1 illustrates possible $\overline{X}$ and R charts for concrete slump. The dotted lines represent the upper control limit (UCL) or lower control limit (LCL). These limits are statistically derived from the process itself, and are not necessarily the same as the specification limits. They represent the limits of chance variation, so that test results which fall outside are interpreted to result from assignable causes.

The control process consists of charting the measurements or test results, studying the pattern of results on the chart, deciding whether or not assignable causes are present, and eliminating or minimizing them if they are. A process which evidences only chance variation is said to be "in control," while a process with assignable causes of variation is said to be "out of control." The technique of control chart analysis, though not difficult, is somewhat of an art. For example, an apparently out of control process may actually have no assignable causes acting, but only require revised control limits or a revised specification. For a detailed discussion of this topic, the reader is referred to References (18), (24), and (51).

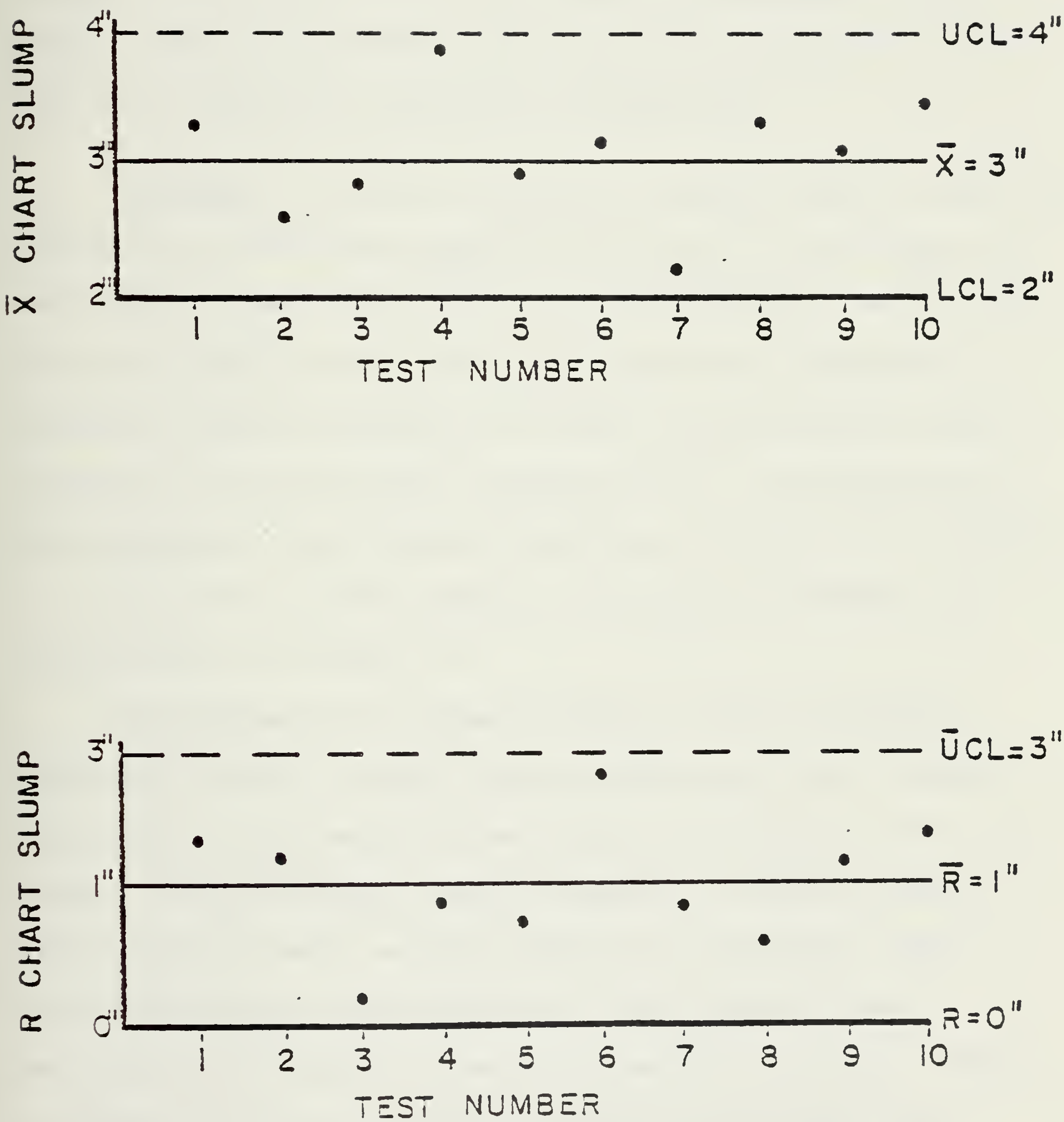

Figure 1. $\bar{X}$ and R Charts

The concept of SQC places a heavy emphasis on process control, and for this reason, it is important that all control efforts be carefully documented. The control charts and all other reports of tests, inspections, or other quality control activities become permanent records which are turned over to the state upon completion of the project. Both the interests of the state and the contractor are well served by a conscientious approach to documentation.

Acceptance. An axiom of statistical quality control is that only the seller can control the quality of his product, but the buyer must have a means to judge the product quality before he pays for it. The acceptance sampling plan provides such a means and is defined as "a systematic inspection procedure to decide, with known risks, whether to accept or reject the product inspected (18)." The significance of this definition is that acceptance sampling is the basis for a decision to accept the lot or item inspected at full price, to accept it at reduced price, or to reject it.

The philosophy of acceptance sampling is that if unbiased, statistical methods, including random sampling, are used to predict the quality of a process, then the contractor is forced to control the process. Under traditional quality programs, no attempt is made to predict quality levels, and very little work is rejected. Under a statistical acceptance plan, there is a high probability that unacceptable work will be discovered and therefore rejected. DiCocco illustrates this point by explaining that in a particularly weak sampling plan with an allowable percent defective of 2.3, if the actual percent defective were 6%, then the plan would reject 50% of the lots

submitted (18). It is obvious that under these conditions, the contractor is forced to control the process.

Acceptance plans, like control charts, are classified as plans for attributes or variables, and the selection of each is based on the nature of the material or process, its quality characteristics, and the probability distribution which describes its variability.

Willenbrock has listed the basic components of an acceptance plan as lot size, number of samples or measurements per lot, sampling or measurement, method of evaluation, and numerical value of specification limits (51). Frequently, provisions for reduced payment are also included.

The material characteristics selected for acceptance are not necessarily the same as those selected for process control. For example, Penn DOT's proposed specification for Portland cement concrete requires process control of slump and acceptance sampling of pavement thickness, air content, and compressive strength (42). Selected characteristics also vary between states. New York, for example, requires both process control and acceptance of slump and air content, but does not formally specify compressive strength (18).

Acceptance sampling plans are the heart of the acceptance process, but it should be pointed out that acceptance also includes close monitoring of the contractor's control procedures. The contractor's own process control plan is usually the basis for such monitoring; however, the inspector is authorized to identify any observed deviation from the specification. It is reemphasized that such an occurrence does not constitute, if handled properly, assumption of responsibility for process control by the state. The proper

procedure requires the inspector or engineer to only identify the nonconformity, and not to recommend corrective action. It is up to the contractor to determine what changes must be made and to carry them out.

Assurance Sampling and Testing. Thus far, highway construction quality control has been described as a two-tiered approach of process control and acceptance. At least two states, West Virginia and Pennsylvania, have a three-tiered system, the third tier being "assurance sampling and testing" or "quality assurance sampling and testing." The term quality assurance (QA) implies the all-encompassing activity of ensuring that construction is satisfactory, and includes both process control and acceptance. It is in this sense that assurance sampling and testing independently evaluates the quality of materials and work in place as a means of measuring the success of process control and acceptance.

The purpose of the assurance program is not control or acceptance, but a way of impartially reviewing the construction to decide if specifications and procedures are effective. It is a feedback system to ensure that changes, when necessary, can be made. In Pennsylvania, to ensure that the assurance process is impartial, the sampling is conducted by personnel from the Bureau of Materials, Testing, and Research who are not involved in acceptance. The testing is also performed in a state laboratory which is not used for acceptance purposes.

Organization and Management

The organization and management of highway construction quality control is discussed by educators and researchers strictly in terms of

the combined contractor and state agency effort. This total effort, called quality assurance, is managed by the state, but carried out as a partnership between the agency and the contractor.

Using Penn DOT's QA program as a model, the quality effort is organized in three tiers--process control, acceptance, and assurance.[1] Process control is carried out by the contractor; acceptance is accomplished under the direction of one of eleven district engineers; and assurance is carried out by the Bureau of Materials, Testing and Research. The contractor's operations, while not directly controlled by the district engineer, are conducted under his supervision. The district engineer in turn is governed by specifications and procedures promulgated by the Bureau, but is not directly supervised by the Bureau. Finally, the Bureau conducts assurance testing, independent of the contractor's or engineer's operations, for the purpose of ensuring the adequacy of existing procedures. It is a checks and balances system which places great reliance on the individual capabilities of each of the three organizations.

The philosophy of quality control management, again from the "total effort" point of view, is that a close working relationship between the members of each organization is essential to a successful program. This is especially true of the contractor and engineer association, where it is required that all process control inspections be witnessed by the engineer, and all acceptance inspections be observed by the contractor. The engineer must administer the contract

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[1]Mr. Robert Nicotera, Research Engineer, Bureau of Materials, Testing and Research, Pennsylvania Department of Transportation, in a personal interview, April 15, 1977.

in a professional and equitable manner, yet has the authority and flexibility to deviate from the specifications when circumatances warrant such action.

Standard specifications and technical reports on SQC make no attempt to suggest the organization or management techniques which should be applied within a contractor's organization. This is in contrast to nuclear power plant and Navy programs, which place a great deal of emphasis on the way a contractor runs his quality system. Highway programs place the emphasis on statistical methods allowing the contractor complete flexibility to organize and manage as he sees fit, so long as the specifications are met.

Summary and Conclusions

Traditional highway quality control systems have produced good quality roads through reliance on recipe type specifications and experienced inspectors and engineers who both control and accept the construction. Extensive testing in the early 1960's reveals that sampling and testing methods were not effective in determining the quality attained. Federal and state agencies decided that statistical quality control procedures were needed to provide a more realistic and equitable basis for construction and acceptance of highways.

An SQC system involves the development of statistical end result specifications by the state highway agencies; process control by contractors; acceptance sampling and testing by the state; and, as an option, assurance sampling and testing also by the state. The emphasis is on the division of responsibilities, with a close working relationship desirable.

The strongest feature of SQC is that it recognizes a time honored principle in manufacturing that the only party qualified and capable of controlling the quality of a product is the producer. It will be shown in later chapters that this principle is a key factor in nuclear and Navy programs.

Another strong feature of SQC is its recognition of the inherent, random variability of materials and processes, and its ability to define nonrandom, assignable causes of variation. This recognition permits the development of realistic contract requirements as well as an equitable administration of the contract.

From the contractor's point of view, the performance of process control allows him to better manage the construction. The end result specifications give him more flexibility in selecting equipment and choosing construction methods. It is logical to conclude that a greater opportunity to manage his own affairs will ultimately lower the contractor's costs.

From the state highway agency point of view, the establishment of statistical acceptance formulas permits a more objective inspection process, and fosters a more cooperative working relationship between the state and the contractor. It is expected that release from the burdensome responsibility for process control will ultimately reduce state inspection costs.

As of 1976, 33 states have instituted or are planning to institute SQC programs; however, the first years' results of existing programs have gone undocumented in current literature. There is a need for feedback on the problems and successes thus far achieved in highway SQC. There is also a need for an explanation of the

disadvantages of SQC which have prompted 17 states to decide not to implement the new programs. With this information readily available, organizations contemplating a switchover will be able to benefit from the lessons of others.

The data currently available has led this writer to the conclusion that the application of statistical methods to highway construction is a logical and progressive undertaking which is applicable to other construction areas as well. It represents an overall approach to quality which is indicative of the systems approach.

CHAPTER III

NUCLEAR POWER PLANT QUALITY ASSURANCE

The construction of nuclear power plants in the United States is accomplished under the supervision of electric utility companies. Most utilities are independent, publicly held corporations; but, because they do not compete with each other, and are in a sense legal monopolies, their operations are tightly regulated by government. One regulation is that the utility's current rate structure cannot be used to finance the construction of new power plants.

Utilities obtain funds for construction from previously earned profits, investors, and loans. It is estimated that a typical plant may cost as much as two billion dollars (23), and take up to ten years to complete (52). Due to the high price of construction, and the absence of relief from rate increases, utilities must devote a great deal of effort toward ensuring that construction is as efficient as possible. Extraordinary cost and schedule control systems have been instituted in a situation where delay damages may be measured in millions of dollars per day.

In such a climate, it would appear that quality assurance (QA) would be of secondary importance to cost and schedule control; however, public concern for nuclear safety, with resultant legislation and regulation, has created a situation where pressure to meet quality assurance standards is equal to or greater than the urgency to meet cost and schedule goals. The QA standards are, in fact, mandatory, so

that failure to meet them can result in the withholding of a license to operate a plant.

Due chiefly to federal law, the emphasis on quality assurance in nuclear construction is greater than that in any other segment of the construction industry. To meet QA requirements, utilities have been required to develop comprehensive programs which require attention to these matters during all phases of a power plant project. As with highway construction, nuclear construction quality assurance can be discussed in terms of planning, procedures, and organization and management.

QA planning encompasses the activities of all parties involved in a nuclear project. The development of utility, contractor, architect-engineer, and equipment supplier QA programs, the preparation of applications for licensing, and the development of contract documents (plans and specifications) are all planning activities.

QA and QC procedures are concerned with the implementation of specifications and programs. In nuclear construction, there are various levels of QA, each of which has its own set of procedures. These levels include construction, quality control, quality assurance, and NRC inspection and audit.

Organization and management of QA programs receives a great deal of emphasis in the regulations and in industry attitudes. The regulations require that these matters be specifically addressed in license applications and in the program descriptions. The industry attitude is that a well-managed QA program will prevent costly rework of deficiencies in an efficient, cost effective manner.

The purpose of this chapter is to describe how the nuclear industry meets its quality objectives through planning, procedures, and organization and management. The first step is to provide a background of the purpose for and development of QA in nuclear construction.

Background

The first commercial nuclear power plant at Shippingport, Pennsylvania, became operational in 1957 (23). By 1969, when the Atomic Energy Commission (AEC) introduced its quality assurance criteria, there were 16 operable plants in the United States and another 48 under construction (29). In 1976, there were 61 operating plants and an additional 176 planned or under construction (45). Nuclear construction is clearly a new field of endeavor, each aspect of which is in a developing phase.

The birth of nuclear construction QA, as it is known today, occurred on April 17, 1969, when the AEC published Appendix B to 10CFR50 (Title 10, Atomic Energy Part 50, Licensing of Production and Utilization Facilities: Code of Federal Regulations) entitled "Quality Assurance Criteria for Nuclear Power Plant." Known simply as "Appendix B," this document provides a list of 18 QA criteria which are the basic guidelines for all QA activity.

In the years prior to 1969, QA programs, as such, did not exist. The emphasis was on new technology, and the quality assurance needed to attain proper performance was regarded as a management judgment (35). Unfortunately, the judgment was not always correct; in some cases, such items as leaky valves and a leaking reactor vessel were not discovered

until they were installed (35). It was under these conditions that the AEC began developing standards which culminated in the publishing of Appendix B.

The only objective of Appendix B and the most important objective of QA programs in general is the assurance of safety through proper design, construction, and operation of power plants. The basis for the safety objective is stated in the introduction to Appendix B, which is reprinted in Reference (53):

> "Nuclear power plants include structures, systems, and components that prevent or mitigate the consequences of postulated accidents that could cause undue risk to the health and safety of the public."

The aim of QA is to ensure that accidents do not occur by ensuring that the structures, systems, and components are free of defects.

The development of QA guidelines did not end with the publishing of Appendix B, and starting in 1972, the AEC began an intensive effort to spur industry compliance (34). This effort included the development of additional regulations, direct inspections of project operations, and emphasis on the necessity for QA and QC personnel to have authority and organizational freedom in their assigned tasks. Also included were a series of regional conferences to educate personnel and exchange ideas. After the disbanding of the AEC in 1974, the newly created Nuclear Regulatory Commission (NRC) continued to regulate and enforce QA policies.

While the key objective of QA is safety, a secondary goal or byproduct is the reliability of operation of the plants which hopefully will meet or exceed expected levels (53). A major concern of utilities, with both fossil and nuclear fueled plants, is the high cost of outages

due to equipment malfunctions; there is, however, disagreement in the literature as to the effect of QA programs on reliability. In 1976, the average capacity factor of a nuclear reactor was about 60% (45), a figure that is regarded as unacceptable by any standards (34, 45, 53). General Public Utilities, however, reported factors of 70% and 81% on two of its plants in 1975, and Wilson (53) has attributed the difference between these factors and fossil fuel plant capacities, which average 60%, to effective QA programming. By contrast, Muntzing (34) states that such comparisons are meaningless because neither fossil fuel nor nuclear capacity factors are good enough.

Whether or not the reliability of a nuclear power plant is related to quality assurance, the fact that the nuclear safety record has been nearly perfect (34), while reliability has not, is somewhat anomalous. According to NRC's Rusche, it means that QA programs are unbalanced (45), and that more attention to "doing it right the first time," and stronger support from top management is needed.

In summary, QA in nuclear construction has been successful in its primary goal of public safety, but is still in a state of development with regard to its efficiency and total objective of safety and reliability. In contrast to highway construction SQC, which is encouraged by the federal government but not required, nuclear construction QA is not only mandatory, but is tightly regulated by the government. In nuclear construction, as in highway construction, the prerequisite to effective quality control is an effective quality control program. Before the topic of nuclear programs can be developed, however, it is necessary to understand the regulatory requirements.

Regulatory Requirements

Before a utility can operate a nuclear power plant, it must obtain a license from the NRC. A first step in obtaining a license is the preparation of a preliminary safety analysis report (PSAR). The PSAR deals with all aspects of a power plant project. A significant section addresses the subject of quality assurance. The utility and its A/E, contractor, and component suppliers all may participate in the writing of the PSAR; but even if they do not, they are each required to comply with its provisions throughout the life of a project.

The function of Appendix B is to provide the QA guidelines from which an acceptable PSAR QA program may be written. The preparation of the program document, unlike the optional highway QA plan, is a mandatory requirement for the utility. Appendix B also serves as a reference for the development of standing QA programs or manuals within the various utility, designer, constructor, and supplier organizations. These manuals, in turn, may serve as the bases for PSAR programs.

The intent of the 18 criteria of Appendix B is to cover all possible aspects of a project where deficiencies in quality could lead to a safety hazard. Consequently, the QA activities are not limited to construction, but include assurance that the design is correct and will result in a safe structure, assurance that materials are purchased, handled, shipped, and stored properly, assurance that erection and installation of materials are correct, and assurance that work (including design) is inspected and tested correctly. The criteria are titled as follows:

1. Organization
2. Quality Assurance Program

3. Design Control
4. Procurement Document Control
5. Instructions, Procedures, and Drawings
6. Document Control
7. Control of Purchased Material, Equipment, and Services
8. Identification and Control of Materials, Parts, and Components
9. Control of Special Processes
10. Insepction
11. Test Control
12. Control of Measuring and Test Equipment
13. Handling, Storage, and Shipping
14. Inspection, Test, and Operating Status
15. Nonconforming Materials, Parts, or Components
16. Corrective Action
17. Quality Assurance Records
18. Audits

The criteria are written in very general terms, indicating what must be done, but not how it must be done. A typical example is criterion number 9, "Control of Special Processes" [reprinted in Reference (53)]:

> "Measures shall be established to assure that special processes, including welding, heat treating, and nondestructive testing, are controlled and accomplished by qualified personnel using qualified procedures in accordance with applicable codes, standards, specifications, criteria, and other special requirements."

Wording, such as "measures shall be established," and terms, such as "qualified personnel" or "qualified procedures," are scattered

throughout Appendix B. In addition, several criteria make a point of requiring that inspections be performed by persons other than those responsible for performing the work.

The lack of specificity in the criteria, such as in the above example, has led to varying interpretations, and difficulties in implementation by utilities, contractors, and designers. To alleviate such difficulties and to clarify any ambiguities, a number of professional organizations have published their own standards which interpret 10CFR50 and provide aditional guidance. The number of guides, codes, and standards is in the hundreds and the information so extensive that probably no single person could remain current in all of the requirements (53).

Despite the wealth of information and regulatory data, the dominant theme of Appendix B remains clear. Quality assurance requires planning in the development of programs; management and organization so that quality and production functions are separated; and procedures which provide assurance that work is accomplished and documented in accordance with applicable regulations.

The regulatory requirements of nuclear power plant construction are analogous to the principles of statistical quality control in highway construction in that each provide the basis for the development of quality programs, and each encourage contractor responsibility for process control. They are quite different in their approach to quality control, however, with SQC placing heavy reliance on scientific and mathematical principles, and nuclear regulations putting reliance on tightly managed control, inspection, assurance, and audit. These

aspects of nuclear QA as well as further comparisons with highway QC will be explored later in the chapter.

As explained earlier, the purpose of the regulatory requirements is to provide guidance to the utilities, constructors, and designers in the preparation of their QA programs. It must be emphasized, however, that although many of the codes and standards are intended to be clarifications, others have expanded quality requirements so that confusion as to interpretation still exists. As a result, a consensus among members of the industry as to what is necessary in a QA program has not been reached (12), hence, program contents vary. The intent of this chapter is to provide a generic overview of QA; therefore, a comparison of individual programs will not be attempted. Much of the source material for this discussion has been obtained through site visits to the Susquehanna Steam Electric Station near Berwick, Pennsylvania. A comparison of information received through personal interviews at Susquehanna with references from the literature indicates that the Susquehanna QA program is representative of industry practices.

QA Programs

In its regulations, the NRC emphasizes that the owner utility is primarily responsible for quality assurance; and, although a utility may assign many QA responsibilities to others, it is still accountable for whatever takes place. The NRC's policy is to determine whether or not a utility's program complies with its guidelines, and then conduct periodic inspections for the purpose of verifying compliance with the program. This means that if a program's requirements are more stringent than the regulations, the utility will still be held to those

requirements. Under these circumstances, it is in the best interests of the utility for the designer, constructor, and suppliers to each participate in the program development.

The practice of evaluating an organization according to compliance with its own program is common to highway and nuclear construction. The requirement for a highway contractor to write his own program is optional, however, the NRC's requirement in nuclear construction is mandatory.

The first task of a QA program is to define the items of construction to which it applies. The NRC is concerned only with safety related construction; therefore, the utility's formal program must list the construction items which, if deficient, could lead to a nuclear accident. These items are referred to as "Q-listed" items and include plant components related to the nuclear reactor, its structural containment, and critical support systems. All other ("non Q-listed") construction is handled by a separate quality control system which will be discussed subsequently.

In a nuclear program, the terms "quality assurance" and "quality control" take on distinct meanings. As defined by 10CFR50 Appendix B [reprinted in Reference (53)],

> "'quality assurance' comprises all those planned and systematic actions necessary to provide adequate confidence that a structure or system will perform satisfactorily in service. Quality assurance includes 'quality control,' which comprises those quality assurance actions related to the physical characteristic of a material, structure, component, or system which provide a means to control the quality of the material, structure, component or system to predetermined requirements."

In practice, QA and QC represent separate organizations, departments, or groups with the QA group evaluating the QC group's

performance. A functioning QA program, in fact, contains many layers or levels of quality activity, each representing an individual group, independent in its organizational structure, yet dependent in certain respects on the functions of the other groups.

The cost of removing and replacing deficient work is high in any type of construction; therefore, the concept of "doing it right the first time" is universal because the prospect of having deficient work detected is real. In nuclear construction, the existence of QC and QA organizations ensures that deficiencies will be detected, so there is a great deal of emphasis on correct performance of work. The efforts of the craftsmen and their supervisors to "do it right" is the first level of quality assurance, and due to the high cost of reworks, in terms of time and money, this aspect of QA is the most vital to a successful project. It should be recognized that this first level of attention to quality exists for both the prime contractor and his subcontractors. Each organization is required to take positive steps to ensure that its work is properly performed.

The second level of quality assurance is "quality control," which involves the first line of inspection. The purpose of QC is to verify that all work conforms to approved plans and specifications through inspection and surveillance of work in process. It is expected that QC activities will uncover nonconforming work; therefore, an additional QC function is to document deficiencies and take follow up action to ensure that they are corrected.

The third level of quality assurance is "quality assurance," which carries both a generic and specific meaning. Generically, it refers to all activities related to quality; specifically, it refers

to the activities of a group separate from the QC or construction group which ensures that QC and construction items have been carried out correctly. The methods of accomplishing this are monitoring and auditing, terms which will be defined in a subsequent section.

The responsibility for QA may be assigned to the constructor, designer, or an outside agent; or the utility may assume the duties itself. In either case, due to NRC pressure for the utility to assume a greater role in the process, the utility is likely to maintain its own QA organization. In the cases where others have been formally assigned the function, the utility effort becomes a fourth level of quality assurance which verifies that the other groups are complying with their programs.

The various levels of quality action and verification create a system of checks and balances which is the heart of QA programs in nuclear construction. In contrast to highway programs which rely on mathematical principles to achieve statistically derived quality levels with tolerances, nuclear programs rely on forceful management and organizational techniques to achieve quality levels based on safety considerations with very few tolerances allowed.

With safety as their stated objective, quality assurance programs have been successful, as the near perfect safety record of operating power plants attests. Subsequent sections will discuss the techniques by which this is brought about. The topic of reliability as a quality objective will be considered in a discussion of non Q-listed quality control.

QA Planning

Quality assurance planning is an activity that occurs throughout the life of a project, including predesign, design, and construction phases. The effort is continuous because "fast tracking" or phased construction, whereby construction commences before the design is complete, is generally employed in nuclear projects. Updated modifications to the QA program, including procedures and instructions, must be developed concurrently with design and construction.

The first planning activity involves the preparation of the QA program which will be incorporated into the PSAR. As mentioned earlier, the various participating firms (contractor, designer, etc.) may assist in the original program development, but whether or not they do, the information contained therein must become the basis for each organization's QA manual. The QA manual is defined as management's statement of policy specifying how each of the criteria of Appendix B and other applicable regulations is to be met (30). The format of a manual is generally in two parts, the first containing an overview of the program, and the second containing detailed procedures and instructions for implementation.

Although the overall objective of the program is safety, the QA manual has the more immediate goal of providing the framework within which the objective can be achieved with minimum conflict and maximum efficiency. McMahon (33) has stated three essentials of this stage of quality planning:

1. minimizing subsequent construction problems as a result of poorly defined quality assurance requirements.

2. making personnel aware of the technical and control requirements prior to work being performed, thereby reducing quality problems.

3. achieving adequate control with a minimum of personnel.

The development of the manual as a management planning activity begins with a decision regarding how the QA functions will be structured. This refers to the various levels discussed in the previous section. The method of structuring the system is based on the extent to which a utility wishes to become involved, and on the unique capabilities of the participating organizations.

The utility's knowledge of who its designer, prime contractor, and major suppliers are at the predesign stage is possible due to the fact that most major contracts are let on a "cost plus" basis. This means that: (1) completed plans and specifications are not a prerequisite to retaining a contractor, and (2) the contractor can be retained as a consultant before the start of construction.

Following the decision regarding the system's structure, the utility must "align the quality assurance requirements as contained in the 18 criteria with a given scope of participation, and identify which requirements apply to each participant (9)." At this point, the requirements for the contractor and suppliers are translated into specifications which become contract requirements. The specification provisions can be expressed through reference to Appendix B, industry standards, or approved company standards, or they may be written out completely with specific references (9).

The completed or partially completed set of specifications for a particular item of construction is the basis from which detailed

procedures are written. The writing of procedures is the function of the quality engineer who may be in the employ of the designer or the constructor. He must obtain technical requirements and safety classifications of work items from the designer, and produce documents which provide guidance as to the level of quality desired and where the emphasis on quality should be put. Tentative procedures are reviewed by the constructor to familiarize his personnel with the requirements, to resolve procedural problems between quality groups, and to resolve technical problems or misinterpretations (33). This review process takes place during the planning stages so that potential QA difficulties can be resolved before construction starts.

It is noteworthy that the setting of quality levels is not considered a QA planning activity. It is recalled that in highway construction, an important planning activity is the setting of realistic target quality levels based in part on statistical analysis. Nuclear quality planning, on the other hand, considers quality levels only from the point of view of execution. There is no attempt to set tolerances, and little consideration of variability. The philosophy is that effective procedures and strong management will produce zero defects. Quality levels are based in part on statistical analyses which predict the probabilities of nuclear accidents, but this type of analysis is not an application of statistical quality control.

The procedures developed by the quality engineer involve both QA and QC, and are routinely delivered to these groups for implementation as design and construction proceed. While most implementation activities come under the categories of Organization and Management,

and Procedures, there are planning activities, as well, which are carried out on a continuing basis.

Quality planning activities during construction include manpower planning, training, and scheduling. Manpower planning primarily involves the QC organization which is the largest of the quality groups. The construction sequences of most Q-listed work items involve hold points beyond which construction cannot proceed until specific quality control inspections or tests have been made. To prevent schedule delays it is vital that the QC organization be prepared to conduct such inspections or tests; therefore, planning is required to ensure that adequate numbers of qualified QC personnel are available.

The industry standard concerning training, entitled "Qualifications of Inspection, Examination, and Testing Personnel for the Construction Phase of Nuclear Power Plants," is specific in its statement of planning requirements:

> "Plans shall be developed for assigning or staffing and training an adequate number of personnel to perform the required inspections, examinations, and tests and shall reflect the schedule of project activity so as to allow adequate time for assignment or selection and training of the required personnel. The need for formal training programs shall be determined, and such training activities shall be conducted as required to quality personnel responsible for inspection, examination, and testing . . .(5)"

Although utilities and contractors are able to attract experienced QA or QC inspectors, there will undoubtedly be a need to hire partially qualified or inexperienced personnel. For this reason, a training program must be planned and implemented before construction starts.

Quality assurance training involves each level of quality activity, including construction itself. Craftsmen in selected trades

must be certified, and for the inexperienced, certification must follow a well-planned training program. A significant feature of nuclear QA is that inspectors must be certified in each area that they inspect. This requirement enhances the professional esteem of the quality personnel and promotes a good working relationship between groups.

The final planning activity to be discussed is scheduling. The QC and QA organizations are each charged with the responsibility of ensuring that all Q-listed construction is inspected and verified as acceptable. Careful scheduling is required to avoid missing any areas, and to ensure that construction delays caused by lack of inspection at hold points do not occur. An important part of the scheduling process, therefore, is being aware of the progress of construction at all times.

QC activities are generally scheduled on a weekly and monthly basis, while QA affairs, which are not as directly involved with day-to-day construction events, are scheduled on a monthly and semiannual basis.

QA planning for suppliers closely parallels the construction planning outlined above. QA planning for design involves the establishment of a quality organization within the architect engineer firm, and the development of procedures with which quality personnel can review the design as it proceeds to verify that it has conformed to the regulatory requirements.

The regulations which govern nuclear power plant construction require that every foreseeable activity or event be preceded by a conscious planning effort. The planning effort, in turn, must be documented in the form of written programs and written procedures. Quality assurance planning follows this pattern and, in addition, is

concerned with manpower planning, scheduling, and training. The best planning effort is to no avail unless properly implemented. The next section provides a discussion of QA procedures and their implementation.

Quality Procedures

QA procedures are the vehicles with which quality objectives are achieved. For this reason, virtually every important task is supported with a written document specifying what is to be done, how and under what conditions it is to be done, and how it is to be documented. For example, Three Mile Island Unit 2 nuclear power plant in Middletown, Pennsylvania has nearly 50 written procedures ranging in length from a few pages to several hundred pages (53). A listing of the titles to the Three Mile Island procedures has been provided in Reference (53). Ten are listed below to illustrate their scope and detail.

1. General Construction and Structural Concrete
2. Vendor Surveillance
3. Records and Filing Systems
4. Quality Assurance Surveillance Plan
5. Quality Control and Inspection Plan
6. Drawing, Specification and Document Control
7. Internal Audits and Response to Owners Audits and A/E Surveillance Reports
8. Final Acceptance Inspection
9. Control of Nonconforming Conditions
10. Work Stoppage
11. Welding Control
12. Quality Control Personnel Training and Qualifications

While the above list refers to QA and QC procedures only, a far more extensive set of procedures governs the work of the construction forces. Construction procedures are designed to ensure uniformity by stipulating that similar operations be conducted in a prescribed manner. Although constructors often have the opportunity to develop their own procedures, the fact that the procedures must incorporate the various regulatory requirements has the effect of limiting a contractor's flexibility of construction methods. The procedures and specifications thus represent the recipe type described in Chapter II. In this respect, the highway industry and nuclear industry have taken somewhat opposite views: the highway industry has opted to focus on the end result of construction allowing the contractor to choose his own means and methods, while the nuclear industry has chosen to focus on both method and results, with the conviction that if the methods are correct, the results will follow.

In nuclear construction, the construction group is clearly responsible for process control, despite the restrictions on its flexibility. Although its work is closely scrutinized by the QC and QA groups, no attempt is made by these latter groups to supervise construction operations. In this respect, both highway and nuclear industries are similar in their recognition that only the contractor can control the process. They are also alike in that they have some flexibility in their process control techniques. The highway contractor generally relies on control charting and other statistical techniques, but has the option of using other methods subject to state agency approval. Similarly, the nuclear construction group is constrained by

procedures but many employ additional measures, such as inspections or tests, to ensure that procedures are carried out.

The concept of variability in materials is significant in the statistical quality control of highway construction; yet, the subject is virtually ignored in the nuclear construction literature. The specificaitons for nuclear power plants generally set minimum quality levels which the contractor, through process control, is required to attain. There has been no universal testing program to arrive at attainable target quality levels with realistic tolerance levels; therefore, the contractor is required to establish his own target levels to assure that minimum levels are attained. The near certainty of detection and rejection of nonconforming work coupled with the very high cost of rework necessitates sufficiently high target levels so that risk of nonconformances is minimal. This, of course, markedly increases the cost of materials. An illustration of this type of process control exists at the Three Mile Island nuclear station, where a concrete design mix yielding a compressive strength of 6250 psi is used to ensure that the specified strength of 5000 psi is attained (52).

Quality Control

At the Susquehanna construction site, the quality control staff numbers 83. The total work force on site, including support personnel (clerical, security, etc.) approaches 3000. These figures are considered typical for a plant during the peak construction period. The assigned task of the QC group is implementation of the quality

control program through quality verification inspections, and surveillance of subcontract work.[2]

There are four classifications of quality verification inspections which are illustrated in Figure 2. The first, receipt inspection, is a check to ensure that incoming materials and components comply with specifications. This type of inspection would generally apply to items to be stored on site; however, materials such as concrete or select fill are also subject to inspection upon receipt. In the case of concrete, the inspection process may involve visits to the batch plant to inspect the component materials. The regulations, for instance, require that all such materials be traceable, that is, that their source be identified and documented.

The second classification is the installation inspection which applies to the accomplishment of any work item, such as the setting and connection of equipment or components, the erection of materials, the placement of concrete, the compaction of soil, etc. Within the installation inspection classification, there are a number of inspections, verifications, and tests which, in the aggregate, cover all construction activity. For example, concrete construction includes two subclassifications, "preconstruction verification" and "inspection of concrete construction" (8).

Preconstruction verification is a check to ensure that materials inspected during the receipt inspection have not been damaged during the interim period. It consists of a visual examination of materials,

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[2] Mr. Gary Shrader, Project Field Quality Control Engineer, Bechtel Power Corporation, in a personal interview, June 21, 1977.

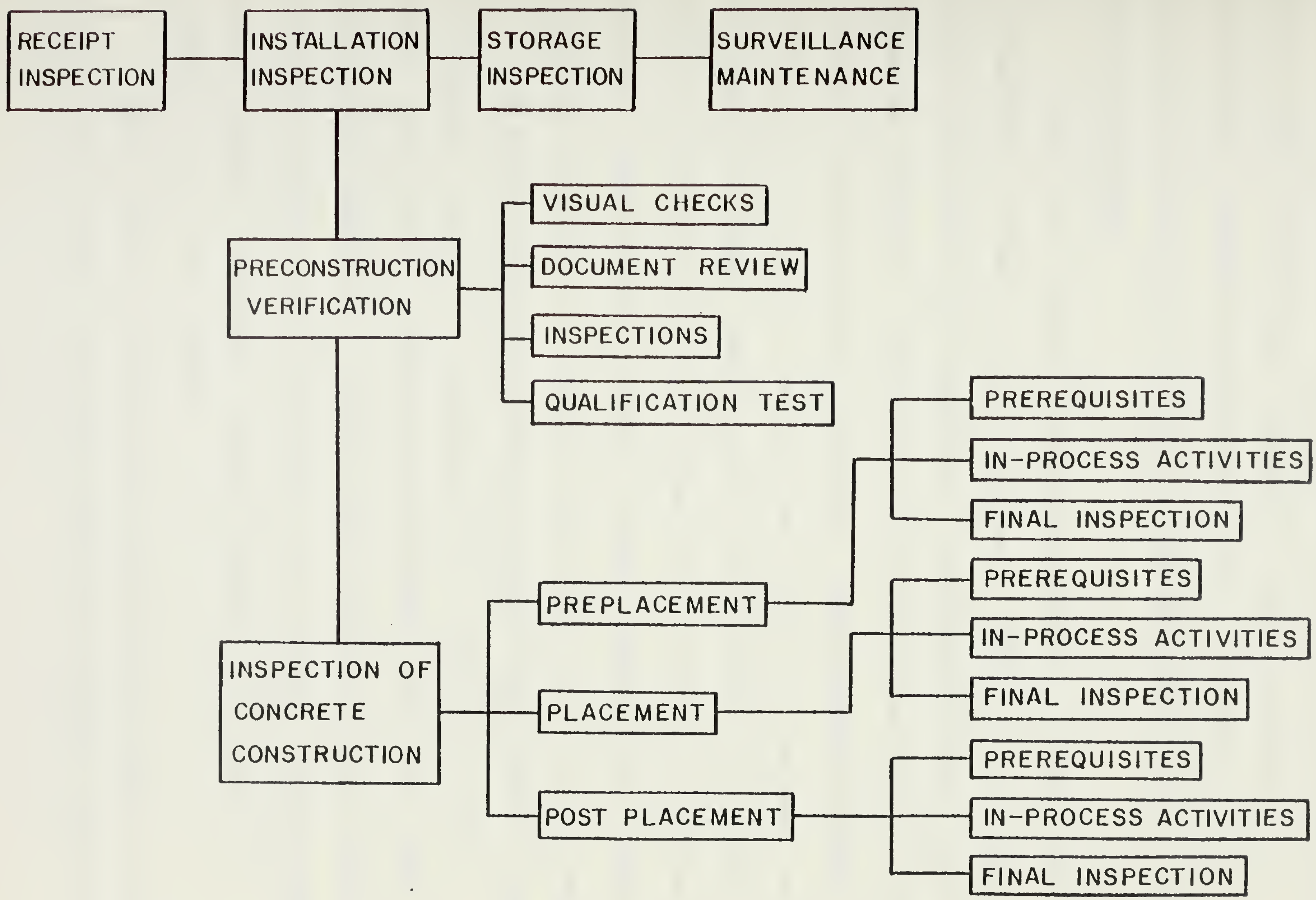

Figure 2. Components of Quality Verification Inspection

a review of documentation of previous tests and inspections, and inspections to verify that the construction group is prepared to control the various processes involved (placement and splicing of reinforcing steel; mixing, transporting, placing, and curing of concrete; etc.). In addition, a number of qualification tests of component material properties are performed in accordance with applicable industry (ASTM and ACI) standards.

Inspection of concrete construction consists of three phases: preplacement, placement, and post placement. Each of these phases is further broken down into prerequisite, in-process inspection, and final inspection activities. Prerequisite activities for each phase include a review of drawings, specifications, and other pertinent documents, such as inspection reports, and previously issued noncompliance reports. The checking of plans, specifications, and the project file, prior to making a field inspection, is the type of activity which would come under the heading of "good practice" in most segments of the industry. In nuclear construction, it results from a detailed, written procedure.

In-process inspection activities include visual checks of work in progress. During the preplacement phase, construction joints, forms, reinforcement, and embedments are checked, and in some cases measured for compliance. Placement phase activities include checks of placement techniques and consolidation. Post placement checks examine slab finishing, form removal, repair of defects, curing, and the loading of structural concrete.

Final inspection activities are further visual checks to verify certain of the actions accomplished during the in-process inspection.

The above visual inspections, accomplished by the QC group, are complemented by in-process tests. These, as well as qualification tests, are generally performed by an independent testing agency under the supervision of the construction group. The QC group, in turn, reviews the test reports after each of the three process phases.

The final step in the installation inspection process involves a review of previous inspection activities to determine if they have been completed without any exceptions. The prerequisites, in-process inspection activities, and final inspection activities, as well as the review of test reports and exceptions for each phase (preplacement, placement, and post placement) are included in formal, prepared check lists. The completed check lists become inspection reports (IR's), which are important parts of QA documentation.

The third classification of quality verification inspection is the storage inspection. In nuclear construction, a great many materials are ordered and received well before they are required for construction. The purpose of storage inspections is to ensure that materials, supplies, and components are properly stored and protected prior to use.

The fourth and final classification is surveillance of maintenance. Due to the length of a nuclear project (up to ten years), installed components and equipment may be idle for a long time prior to start up. To ensure that deterioration does not occur, the construction group is responsible for a maintenance program. The QC group conducts surveillance to ensure that the maintenance program is properly conducted.

The second aspect of QC implementation, surveillance of subcontract work, should be mentioned. Because subcontractors, as a

rule, are required to provide their own quality control system, it is not necessary that the prime contractor's QC group duplicate the effort. It is required that the subcontract QC effort be verified, however, and this task falls to the prime contractor. As with all QA and QC activities, the surveillance of subcontract work must be performed and documented in accordance with written procedures.

Although the regulatory requirements do not consider variability from a statistical viewpoint, they do recognize that defects will occur, and require that procedures for handling nonconforming work be implemented. The formal procedure in both QA and QC organizations involves a five-step process: detection, report of nonconformance, segregation and identification, disposition, and documentation and notification (28). There are no provisions for reduced payment as in highway construction, but considerable judgment is permitted in the handling of defects.

Nonconformances may be detected by anyone, although they generally are discovered by either the QA or QC inspectors. The formal procedure requires that a written report be submitted to the construction supervisor and the owner utility; however, in practice, minor (trivial) defects are handled verbally with no report. There are also provisions for minor defects to be documented by informal, written reports which are not sent to the utility.

If a formal report is filed, the nonconforming work item must be tagged, and removed from production. If the defect is serious, it may be necessary to halt production or stop work. Each QA or QC organization has the authority to stop work if necessary. The concept

of organizational freedom which makes this possible will be discussed in the next section.

Upon receipt of a report, the construction supervisor reviews any procedural nonconformances for correction, and construction engineers review nonconforming conditions for possible rework (33). At this point, engineering judgment determines whether the defects can be repaired, reworked, or accepted as is. The decision of the construction engineer is subject to approval of the designer's and utility's QA/QC organizations. The final requirement is that the corrective action be taken and properly documented. Follow-up surveillance by the QC and QA groups is required to ensure that this takes place.

In summary, quality control in nuclear construction is a highly proceduralized program of direct inspection and verification of construction operations. As such, it is the first and primary level of acceptance of work in place. Unlike highway acceptance, which relies on statistical acceptance plans, nuclear QC strives for 100% inspection of all processes. While highway acceptance plans focus on the end result of construction, nuclear QC emphasizes each step in the process, including preparation for construction and the end results. Both highway and nuclear programs involve sampling and testing of materials; however, while highway SQC is committed to random sampling, nuclear QC permits either random or representative sampling based on the judgment of the inspector.

Quality Assurance

Quality assurance in its generic sense refers to all quality activities in nuclear construction. The term QA at a construction site, however, refers to specific levels of activity above construction and quality control. As mentioned earlier, the utility may accomplish QA activities with its own forces or assign the work to others; however, in either case, due to NRC pressure on utilities to assume more responsibility, the utility will need a QA organization.

At the Susquehanna plant, the utility and constructor each maintain a QA organization. The constructor's QA group has a staff of nine, while the utility's group numbers eleven. The stated function of each group is the same: to ensure that the QA program is properly executed by monitoring and auditing quality activities. In effect, the QA groups are additional levels of acceptance. All work found to be satisfactory by the QC inspectors is accepted unless either of the QA groups takes exception.

The role of the constructor's QA group is primarily to oversee the activities of the QC group; however, direct observations of construction operations or work in place are also involved.[3] The utility QA group has essentially the same role, with the additional responsibility to oversee the constructor's QA group, and serve as the primary point of contact with the NRC.[4]

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[3]Mr. Ron Lutton, Senior Quality Assurance Engineer, Bechtel Power Corp., in a personal interview, June 21, 1977.

[4]Mr. John Green, Resident Nuclear Quality Assurance Engineer, Pennsylvania Power & Light Co., in a personal interview, June 21, 1977.

The requirement for audits is a specific criterion of Appendix B to verify compliance with the QA program and to measure the program's effectiveness. ANSI defines the audit as follows:

> "A documented activity performed in accordance with written procedures or checklists to verify, by examination and evaluation of objective evidence, that applicable elements of the Quality Assurance Program have been developed, documented and effectively implemented in accordance with specified requirements. An audit should not be confused with surveillance or inspection for the sole purpose of process control or product acceptance (7)."

The audit process involves record and documentation reviews, and visual observations of construction items. A complete audit traces a component or item of work from its time of manufacture to the time when the audit is made; but the auditor may, at his discretion, reduce the scope of an audit to a record check alone, or to a check of a particular phase of a process. Audits are generally scheduled in advance, and the parties to be audited usually receive some advance notice.

QA monitoring is a less formal activity which is usually not preceded by advance notice. Unlike auditing, it does not require formal procedures or check lists. In addition, it involves more observation of in-process construction, and it considers all aspects of a process. For example, monitoring would consider the entire process of a heat exchanger installation, whereas auditing would be concerned with only one aspect, such as electrical connections.

The QA treatment of nonconformances is identical to the five-step procedure described under Quality Control.

The intent of QA is to cover all areas of construction, although in practice, the coverage is much less detailed than QC. Detailed audits do occur, but they represent a spot check of QC and are selected

and conducted at the discretion of the QA Engineer. In general, the higher the level of QA, the more judgmental and discretionary are its activities.

NRC Inspection and Audit

Although NRC activities are not an official part of the utility's program, they are in effect an additional QA level. By law, the NRC is empowered to inspect construction sites, audit QA programs, and enforce the regulations through punitive measures, if necessary. NRC audits and inspections are similar to QA activities in that formal procedures and check lists are used for each action. NRC activities are generally not preceded by advance notice to the utility.

Non Q-Listed Quality Control

The QA organizations and procedures discussed above relate only to Q-listed or safety related construction; however, a significant portion of the work, including such structures as the administration building and cooling towers, is non Q-listed or non safety related. Utilities and constructors are concerned with the quality of this work, but the activities associated with assuring the quality are not called "quality assurance;" nor do the QA organizations, described in previous sections, have anything whatsoever to do with them.

The quality of non Q-listed work is controlled by the contractor's construction group and accepted by the utility's construction personnel under an informal arrangement where the contractor is responsible for materials testing.

It was mentioned earlier that power plant QA programs have had successful safety records, but disappointing reliability factors.

Although there has been no attempt in the literature to fault non Q-listed quality control for the lack of reliability, Rusche (45) has pointed out the conviction of some people in the industry that QA should apply to all important activities, safety related and non safety related.

Organization and Management

The introduction of QA standards in the nuclear industry was initially met by resentment and attempts to "get by" with as little effort as possible (37, 45). In the ensuing years, there has been a softening of negative attitudes due to the realization that "the management tools brought about by quality assurance represent a better way of doing business (27)."

Attitudes notwithstanding, the effect of the regulations and strict enforcement by the NRC has been a recognition that effective QA is a prerequisite to obtaining an operating license. The question germane to this discussion is then, what are the roles of organization and management in bringing about effective QA?

The answer to this question is provided to a great degree by the regulatory requirements which provide guidance and specific directions. Criterion I of Appendix B [reprinted in Reference (53)] contains the basic requirements which are summarized below:

1. The applicant (utility) is responsible for the QA program.
2. The QA work may be delegated to others, but not the responsibility.

3. The authority and duties of QA personnel and organizations must be clearly stated.
4. QA personnel and organizations must have authority and organizational freedom to identify quality problems; initiate, recommend, or provide solutions; and verify implementation of solutions.
5. Management measures are required to insure that QA personnel are independent of production personnel or management.

The above requirements have been interpreted by two additional publications. ANSI N45.2, entitled "QA Program Requirements, Nuclear Power Plants" (6), contains amplifications to Criterion I which are summarized below:

1. QA personnel and organizations must have the authority and organizational freedom to control further processing, delivery, or installation of a nonconforming item, deficiency, or unsatisfactory condition until proper dispositioning has occurred.
2. Organization and assignment of responsibilities must be such that:
   a. attainment of quality is accomplished by personnel responsible for performing work.
   b. verification of quality is accomplished by personnel not responsible for performing work.

3. QA duties should be assigned to those parties most qualified in a particular discipline. QA should not be the sole domain of a single QA group.

Section of NRC Regulatory Guide 1.70, entitled "Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants, LWR Edition, Section 17 - 'Quality Assurance'" [reprinted in Reference (53)] contains further amplifications to Criterion I which are summarized below:

1. QA organization charts, indicating responsibilities for quality of design, procurement, manufacturing, construction, testing, inspection, and auditing, must be included in the QA program.
2. The program must state who has overall authority and responsibility for QA, review of the QA program, and setting and evaluation of QA policies.
3. The measures taken to insure that QA personnel have organizational freedom must be stated.
4. The program must state how QA personnel will have access to higher management levels (with authority to take action).
5. The lowest QA management level at which work can be stopped (if deficient) must be defined.
6. The utility's method of controlling the QA duties assigned to others must be stated.
7. The method of communication to assure coordination of QA activities must be described.

The above requirements are comprehensive, but not so restrictive as to eliminate flexibility in utility management. The NRC has found, moreover, that programs have overemphasized certain areas, such as QA documentation and paperwork, while underemphasizing others, such as effective corrective action plans (45). The key to effective management is seen to be a set of well-balanced objectives, and the commitment of top management to them. These principles are well-stated by NRC's Rusche (45):

> "Our [NRC] experience thus far clearly shows that the effectiveness of quality assurance programs is directly proportional to the knowledge and commitment of senior-management and to their involvement in the definition and implementation of those programs.
>
> "Balance in QA cannot come only from the QA manager or the engineers and craftsmen involved in the activity. Only senior management can assure the priorities and proportion of the QA program, and only management can guarantee its effectiveness."

The thrust of Rusche's argument is that blind or perfunctory conformance to the letter of the regulations is not effective QA; rather, a substantive, logical approach which can only be coordinated by top management results in successful QA.

Utilities and constructors are generally organized by discipline with a field staff supported by a corresponding home office staff. The major field organizations are engineering, construction, quality control, and quality assurance. The organizations are always structured such that quality groups are separate from production groups. The concept of separation of quality control and production within the contractor's organization is basic to a nuclear QA program, yet the matter has received little consideration in highway construction where the contractor's QC technician may report directly to the superintendent.

In a nuclear project, the QA and QC engineers report directly to their counterparts in the home office, not to the jobsite construction manager or project manager.

To achieve their quality objectives, senior managers have emphasized organizational freedom and communications. Organizational freedom in the context of a nuclear construction project means that not only are quality personnel insulated from production functions in the organizational structure, but also that, in practice, they have the freedom to accomplish their tasks without undue pressure from the other groups. It is customary for the senior company officer (utility or constructor) on site to be the construction or project manager, who is primarily responsible for cost and schedule control. As a result of their seniority, these individuals, with the blessing of top management, could, despite what the organization chart said, easily assert authority over the QA and QC personnel. By emphasizing organizational freedom, top managers assure that QA and QC managers maintain the necessary control and authority to perform in accordance with the spirit of the regulatory requirements.

Senior managers have also emphasized the need for good communications (35) due to the fact that the various groups must coordinate their work. In the early phases of a project, there is a tendency for friction to develop between construction and QA/QC groups due to resentment, mistrust, suspicion, and lack of understanding by both parties (37). The top managers of the utility and constructor must eliminate such friction through a commitment to effective communications at and between all organizational levels. In practice, communications result in rapport and close working relationships

between groups, thus making the project a team effort. In reality, there are deficiencies and nonconformances, and stop work orders are issued by QA groups; but if the actions are taken in a spirit of cooperation, and communications maintained, the efficiency of the process can be significantly improved.

Although the quality assurance process has matured in recent years with respect to program implementation and the meeting of safety objectives, industry leaders are largely dissatisfied with its cost effectiveness. Describing current QA methods as "cumbersome and sometimes painful," the Atomic Industrial Forum's Ad Hoc Subcommittee on Elements of Cost Effective Quality Assurance and Quality Related Capital Costs has identified management's role in creating a more cost effective program as that of emphasizing performance through pride of workmanship (25). The committee points out that pride of workmanship and therefore improved productivity can be fostered by a management emphasis on the responsibility of the "doers" for compliance with the specifications, and an integration of documentation and audits into the system so that production personnel understand the relationship of the QA program to the quality of their work.

Clearly, a major difference between the highway and nuclear approaches to quality is the emphasis on management's role in the QA/QC process. The highway SQC approach focuses on the end results of construction, allowing contractors a great deal of flexibility in the organization and management. The nuclear approach focuses on the results and the methods, requiring specific management activities and specific organizational characteristics.

Summary and Conclusions

Quality Assurance in nuclear power plant construction is a recent development which had its formal beginnings with the publication of 10CFR50 Appendix B in 1969. The 18 criteria of Appendix B together with numerous interpretive documents and standards constitute a highly restrictive set of regulatory requirements which govern all quality activities connected with a nuclear project.

The major goal of QA is the safety of power plants in operation through proper design and construction methods. The regulatory approach toward this objective is for utilities to develop extensive QA programs outlining in specific terms the procedures, organization structures, and management techniques to be employed.

The regulations stipulate that several independent levels of quality activity be established as a system of checks to ensure that each QA activity is performed properly. Typically, these levels consist of construction and process control by the contractor; quality control by a separate group within the contractor's organization; quality assurance by a third group within the contractor's organization; and quality assurance by the utility. A further level of assurance is provided by NRC audits and inspections.

The strength of QA is in the detailed and extensive procedures which define exactly how each quality activity, including inspection, testing, and construction itself is to be performed. The procedures are intended to ensure that all work is performed correctly, but if it is not, to assure that deficiencies will be detected and corrected.

The regulations and industry leaders emphasize strong organizations and top management support as prerequisites to effective

QA. Organizational freedom of QA groups and effective communications between construction and QA groups are considered essential to this end.

A comparison of the aspects of highway and nuclear quality control has led this writer to the conclusion that certain aspects of each are applicable to the other. One of the strongest features of nuclear QA is its growing recognition of the key roles of organization and management in the control of quality. It is a fact that the pressures of cost and schedule control can have an impact on concern for quality control unless the functions are separated organizationally with strong backing from top management. The NRC has recognized this fact in its regulations, and nuclear industry leaders have emphasized the point in their papers and seminars. The highway industry has made little mention of it, largely due to its emphasis on end results and testing rather than methods and mangement techniques. It is clear, however, that a situation in which a project superintendent, directly responsible for costs and schedule, is also responsible for quality control, could easily lead to sacrifices of one for the other. It is felt that recognition of the principle of separation of production and control of quality would strengthen highway programs.

One of the strongest features of highway QC is its recognition of variability, and random sampling in its acceptance plans. The apparent reason for the nuclear industry's non recognition of these statistical principles is the overriding mandate of complete safety. It is understood that safety standards cannot be lowered, but it can be proven mathematically that random sampling is a better indicator of safety than representative sampling because it removes bias. Despite

the organizational freedom of QA personnel, the enormous pressure involved when an inspector must stop work for even the smallest variabilities, could create a bias in favor of the construction group to the detriment of safety. Random sampling eliminates the possibility of bias.

Recognition of inherent variability could reduce construction costs significantly by lowering the quality levels which constructors must aim for to assure perfect materials. In concrete construction, target quality levels with tolerances could be set and statistically controlled without sacrificing minimum quality levels.

The main reason for the absence of SQC in nuclear construction is probably the absence of a documented testing program, comparable to the AASHO road test, which would pinpoint the quality levels actually being attained. The excessive cost of building a mock containment vessel and subjecting it to the forces for which containments are designed would appear to eliminate such a program from consideration; however, if the rising costs of construction threaten to eliminate nuclear power as a visible economic alternative, then such a program may in fact become an economic necessity.

CHAPTER IV

THE NAVY CONTRACTOR QUALITY CONTROL PROGRAM

Background

U. S. Navy construction involves the creation of new facilities and the remodeling of existing facilities in support of ships, aircraft, and the shore establishment. Construction projects include piers, airfields, buildings, roads, and industrial facilities. With few exceptions, competitively bid, lump sum contracts are used, and nearly all work is accomplished by civilian contractors. Most design work is handled by civilian architect-engineers, with the balance performed by civilian professionals of the Naval Facilities Engineering Command (formerly the Bureau of Yards and Docks).

The Naval Facilities Engineering Command (NAVFAC) is charged with the administration of all Navy construction contracts, and acts in the same capacity as the state highway agency in highway construction, or the utility in nuclear power plant construction. In practice, and hereafter in this discussion, "NAVFAC" activities, as related to contract administration, will be referred to as "government" or "Navy" activities.

Navy construction contracts, as well as all Department of Defense contracts, are governed by provisions of the Armed Services Procurement Regulation (ASPR). The basis for Navy construction quality control programs is ASPR Clause 7-602.1(a), which states:

> "The Contractor shall (i) maintain an adequate inspection system and perform such inspections as will assure that the work performed under the contract conforms to contract requirements, and (ii) maintain and make available to the Government adequate records of such inspection (17)."

Although the above requirement was instituted in the early 1960's, the Navy continued to employ traditional quality control methods until 1970. At that time, a GAO study determined that Defense Department QC programs should require that contractors be responsible for quality control. A Navy review of traditional practices revealed that government personnel were performing quality related functions that should be performed by the contractor. Such practice encouraged substandard contractors to rely on the government to control their workmanship, and led to problems of "implied consent," whereby construction defects, unnoticed by the government inspector, were assumed to be acceptable. In addition, contract delays were occurring as contractors halted operations to wait for government inspections. Consideration of the above, as well as problems with limited staffing (of government inspectors) and increasing construction costs, led to the establishment of the Navy Contractor Quality Control (CQC) Program in March of 1970.[5]

The thrust of CQC is that the contractor is completely responsible for his work, and as a result, he must engage in an active quality control effort. The program also recognizes the importance of good quality plans and specifications, specific contract requirements for quality control, and active enforcement of contract provisions (16).

CQC Program requirements and guidance for implementation are contained in the NAVFAC Construction Quality Control Manual (16) and the NAVFAC "General Provisions (Construction Contract)" (15), the latter of which are a part of nearly all Navy contracts.

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[5]Mr. Paul Plaisance, Chief Construction Engineer, Naval Facilities Engineering Command, in a telephone interview, July 7, 1977.

The subsequent sections of this chapter highlight CQC Program requirements, and their implementation through planning, procedures, and organization and management. The primary source materials for this chapter are the NAVFAC manual and the author's personal experience as a Navy Assistant Resident Officer in Charge of Construction, responsible for the administration of CQC contracts at the Naval Base, Norfolk, Virginia.

It should be noted that the U. S. Army Corps of Engineers has also adopted a CQC program as a result of ASPR requirements and the GAO study of 1970. The Army and Navy program requirements and implementation procedures are essentially the same with one exception being that while the Navy requires CQC provisions for all contracts in excess of $1 million, the Army has a more flexible policy of evaluating each project individually for possible CQC application.[6]

CQC Program Requirements

The CQC Program includes requirements for both the contractor and the government. In fact, the whole philosophy of the concept is that the effort be mutual rather than a simple shift of government effort to the contractor (16).

Contractor requirements are contained in Clause 79 of the General Provisions, Division 1 of the project specifications, and the technical divisions of the specifications. The Clause 79 requirements are analogous to the eighteen criteria of 10CFR50 Appendix B in that they describe what is expected in general terms. There are eight subparagraphs in Clause 79 which cover the following items:

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[6]ibid.

1. The contractor must establish a quality control organization and system.
2. The contractor must provide a CQC representative to ensure conformance with the contract.
3. The contractor must develop a written CQC Plan.
4. The contractor's inspection procedures must include preparatory, initial, and follow-up inspections.
5. The contractor must meet with government representatives prior to start of construction to discuss CQC matters.
6. The contractor must provide a daily CQC report during construction which certifies contract compliance.
7. Test reports which certify compliance must be provided.
8. All submittals (shop drawings, samples, etc.) must be approved and certified by the contractor.

Also included are specifics regarding the authority and responsibility of the CQC representative, and the content of the CQC Plan.

The parallels between Clause 79 and Appendix B are numerous. Both emphasize organizational freedom and authority of QC personnel; both require written plans; both require three-phased inspection procedures; and both require documentation of QC efforts.

Division 1 CQC requirements amplify the General Provisions and provide modifications based on the needs of a specific contract. The technical divisions of the specifications provide specific details regarding inspection, testing, and the approval of submittals.

Government requirements for CQC programs are contained in the NAVFAC manual. Included are planning guidance for specification preparation and preconstruction activities, and detailed contract administration procedures.

CQC Planning

The first quality planning activity for a Navy contract is a determination of whether or not CQC will apply, according to the $1 million dollar criteria mentioned earlier. The next significant planning occurs during the design phase, as the Division 1 and technical sections of the specifications are written.

The purpose of design phase planning is to provide the framework for the best possible project quality for each work item involved. To this end, it is often decided that certain aspects of quality should be controlled by the government rather than the contractor. Occasionally, the required construction is of a level of sophistication that minimum qualifications for the CQC representative must be included in Division 1. Generally, each section of the technical specifications contains statements describing who (contractor or government) is responsible for quality control, what tests or inspections are necessary, who must conduct them, and what documentation is required.

The technical specifications also contain requirements for shop drawings: what they must contain, and who must approve them. An important aspect of CQC is that the contractor is required to review shop drawings himself, and certify in writing that they conform to the specifications. The purpose of this requirement is to force the contractor's quality control personnel to become intimately familiar

with the details of construction, and, of course, to catch mistakes before construction starts. Occasionally, specific shop drawings are of such importance that the specifications require government approval prior to commencing work. In all other cases, construction may commence upon approval of shop drawings by the contractor's own CQC personnel. Setting forth shop drawing requirements in clear, understandable terms is an important planning activity.

A distinction should be drawn between owner planning activities in highway, nuclear, and Navy quality programs. It is recalled that state highway agencies, at the planning stage, are primarily concerned with deciding which work items are to be statistically controlled, what the quality levels should be, and what the acceptance criteria should be. Utilities planning nuclear projects are concerned with establishing a detailed written program to satisfy the NRC. Navy planners of CQC contracts utilize a standard program (NAVFAC CQC Manual and General Provisions), and determine quality levels in the traditional manner. The standing program requires that all quality be controlled by the contractor; therefore, the planning process is primarily concerned with what the exceptions will be, that is, what the government's QC role will be. It is clear that CQC is essentially a management technique which involves reassigning roles and responsibilities for contractors and the government. Unlike highway and nuclear programs, the Navy standards of quality are unchanged.

Contractor planning for CQC contracts begins during the bidding stage when quality requirements are estimated and included in the bid price. Inspection and testing certainly add to the construction costs, but such increases are offset by savings in government inspection and testing.

The most significant contractor planning occurs between the time of contract award and commencement of work. In this short period of time, the contractor must establish a quality control organization, develop procedures for processing submittals, provide an inspection and testing schedule, and develop documentation procedures. Each of these items, as a minimum, must be included in the CQC plan, which in turn must be approved by the government prior to commencement of construction.

As noted in Chapter II, a highway contractor may have the option of writing his own quality control plan or subscribing to a state agency set of guidelines. CQC plans are mandatory in Navy contracts, and have the effect of forcing the contractor to organize and prepare for his quality activities. The requirement for approval of the plan prior to start of construction is an incentive for the contractor to plan effectively.

The final planning activity is a preconstruction conference between the contractor and government for the purpose of coordinating CQC activities. This meeting is a specific requirement of Clause 79 and covers all aspects of contract administration related to CQC. By reaching a mutual understanding prior to the start of construction, the goal of a close working relationship between government and contractor personnel is more easily met.

CQC Procedures

As with planning, CQC procedures can be divided into contractor procedures and government procedures. Contractor procedures include submittal processing, inspecting and testing, and documentation.

Submittal processing involves the review and approval of all shop drawings, samples, catalog cuts, and test reports to ensure that they

comply with the plans and specifications. To ensure that all required submittals are reviewed, a status log containing a list of all specified submittals is prepared ahead of time. Upon review and approval of submittals by CQC personnel, copies are forwarded to the Navy for filing, and to the jobsite for use in construction. The fact that the contractor does not have to wait for government approval (except when specifically stipulated) is a time saving advantage over traditional architect review and approval methods.

It should be pointed out that the government reserves the right to take exception to a CQC approval, and in addition, the contractor does not have the right to approve contract deviations. These aspects have the positive effect of ensuring contractor diligence in his review, but have the negative effect of delaying progress as the contractor seeks government approval for all deviations, regardless of how minor.

The second aspect of contractor procedures is inspection and testing. Because the specifications specifically state the inspection requirements for each work item, the CQC representative has little flexibility in his activities. As with submittals, all inspections and tests are contained in a status log, and in this case, the list is keyed to the construction schedule. If a critical path (CPM) schedule is used, the inspections and tests are included as activities.

CQC inspections consist of three phases: preparatory, initial, and follow-up. A major objective of CQC is to prevent defects from occurring rather than discovering them after they occur; therefore, CQC representatives are instructed to emphasize the preparatory and initial inspections (16).

The procedures involved which each phase parallel in concept the phased approach of nuclear quality control. The difference is that while nuclear QC programs contain individual procedures for each work item, CQC specifications contain a generic set of procedures which apply to all work items. Basically, preparatory inspections are carried out before work commences to ensure that all preparations have been made correctly. This includes a check to ensure that approved shop drawings have been complied with. Initial inspections are accomplished as soon as a representative segment of work is complete to ensure that initial progress is correct. Follow-up inspections are performed as often as necessary to ensure that performance continues to be satisfactory, or to check to see that defects have been corrected.

An important point about CQC inspection is that the CQC representative has the authority to approve (not accept) construction. This means that, unless specifically stipulated, the contractor need not wait for Navy inspection before "covering up" work in place. This is another time saving advantage to the contractor, which allows him greater flexibility in the scheduling of his work. The role of the CQC representative in approving construction is analagous to the QC group's role in nuclear construction. Each has a great deal of responsibility and authority, yet each is under constant surveillance from above. Navy surveillance of CQC is discussed later in this section.

Testing is an important procedure in CQC, as it is in highway SQC or nuclear QA. The contractor is responsible for this, and usually hires an independent testing agency satisfactory to the Navy. Test reports are reviewed by the CQC representative and their compliance with specifications is certified.

The third aspect of contractor procedures is documentation. All quality control activities must be documented following a logic similar to that of nuclear QA documentation. The immediate objective is that the quality that goes into each work item be recorded for future use. In nuclear construction, the recording must be such that complete traceability is achieved. Even the names of craftsmen performing a specific segment of work are recorded. In Navy construction, documentation is much less extensive, but still seeks to establish, for the record, that all construction has been approved by the CQC representative.

The chief documentation device is the CQC Daily Report. The General Provisions require that this report be filled out each day by the CQC representative, and that a copy be sent to the Navy for information. The report contains a description of work accomplished, inspections and tests (with results), and a list of any definitions noted. In addition, each report contains the following certification:

> "The above report is complete and correct and all material and equipment used and work performed during this reporting period are in compliance with the contract plans and specifications, to the best of my knowledge, except as noted above (15)."

The overall objective of documentation is to impress the contractor and his CQC representative with the seriousness of the Navy's requirement that the contractor be responsible for quality. The reports also serve as a legal record should a dispute over project quality arise.

Although the thrust of CQC is that the contractor assumes responsibility for quality, the quality objective is considered a joint effort. For this reason, Navy procedures during construction

are considered to be as important as contractor procedures. These procedures include enforcement, inspection, and surveillance.

Enforcement of contractor quality control is a contract administration function, which involves steps to correct contractor problems and deficiencies in carrying out his CQC tasks. Corrective actions available to Navy administrators include orders to remove and replace defective work, withholding of payments, orders to remove incompetent personnel, stop work orders, issuance of unsatisfactory performance appraisals upon completion of work, and termination of the contract for default. These measures, although administrative in nature, are analogous to the punitive measures available to the NRC in correcting nuclear QA deficiencies. Their purpose is to provide an incentive for contractor diligence in quality control management.

Navy inspection is an independent examination of construction by Navy inspectors for the purpose of ensuring that all work complies with the plans and specifications. It is carried out by the individual inspector assigned to the project or by a special team of inspectors. The inspection procedure differs from nuclear quality assurance in that its purpose is not to evaluate CQC performance, but is to directly check the construction. Deficiencies discovered are reported to the CQC representative, who takes corrective action.

Surveillance is defined as "a close watch or observation kept over a contractor's inspection system to ensure that it is functioning properly . . . (16)." It is accomplished by the assigned Navy inspector concurrently with inspections. It also differs from nuclear QA in that it is not accomplished according to formal procedures. It is highly judgmental, and conducted at the discretion of the inspector.

Inspectors are advised to conduct extensive surveillance at the beginning of a job, and then reduce it when they are convinced of the CQC representative's competence.

While differing in techniques, Navy enforcement, inspection, and surveillance play the same role as nuclear QA, and highway acceptance and testing. Each system recognizes the importance of quality control by the contractor, but also acknowledges the necessity for owner action to ensure that proper QC takes place. The procedures employed by highway agencies, utilities, and the Navy are quite different. Highway agencies emphasize statistical acceptance sampling and testing, and assurance sampling and testing; utilities rely on tightly controlled formal procedures; and the Navy depends on the judgment of its inspectors and contract administrators.

Organization and Management

As mentioned earlier, CQC is largely a management effort. Consequently, the contract provisions require contractor attention to organization and management. These provisions do not detail the techniques to be employed, but provide general guidelines in a similar, though less extensive, manner to Appendix B in nuclear construction. The key requirements are that the contractor have a quality control organization, and a system to ensure that the requirements are met. Although it is not so stated in the contract, it is emphasized in preconstruction meetings and throughout the duration of the project that active top management support in the contractor's organization is essential to successful CQC. Administrators are alerted to watch for contractor apathy and take corrective action if necessary.

The most important member of the contractor's quality control organization is the CQC representative. It is his duty to execute the CQC plan. To do so properly, he must have sufficient authority. Clause 79 states that he must "be on the work at all times during progress, with complete authority necessary to ensure conformance with the contract (15)." This authority does not include the power to make changes, but does allow him to stop work if necessary to prevent covering up defective work.

The requirements further state that the CQC representative must not be subordinate to the project superintendent, but rather must report directly to an officer of the firm. This is the concept of organizational freedom, which is also important in nuclear QA. The point is to separate those responsible for quality from the pressures of cost and schedule control. This is possibly more difficult to achieve in Navy construction for a variety of reasons. Firstly, Navy contracts are almost exclusively competitively bid with fixed prices and required completion dates. The pressures involved with protecting profits and avoiding liquidated damages for delays are therefore more dominant than those in nuclear construction accomplished under "cost plus" contracts. These pressures have the negative effect of discouraging excessive diligence on the part of the CQC representative, who owes his allegiance to the contractor. To avoid conflicts of interest, contractors should recognize this as a potential problem, and instruct the CQC representative to focus his attention on preventing mistakes, rather than catching them after they occur. With this approach, a diligent CQC representative can contribute to

increased profits and reduced construction time without direct involvement in cost and schedule control.

Additional organizational freedom difficulties relate to the seniority and qualifications of the CQC representative. Although he reports directly to an officer of the firm, the fact that a superintendent may be more experienced and senior in the company, puts the CQC representative at a disadvantage. Navy policy is not to set minimum qualifications for quality personnel, but to reserve the right of approval based on qualifications stated in the CQC Plan. As a result, it is quite possible that a CQC representative will face the challenge of working with a more experienced superintendent. If he is assertive in the discharge of his responsibilities, the effort can be a success; if he is not, he may be removed upon request of the Navy. This potential problem has been largely overcome in nuclear construction, due to the support of top management and the minimum qualifications for QA/QC personnel which are set by the NRC.

In addition to authority and organizational freedom, the contract requires that the CQC representative's duties be limited to quality control responsibilities (including safety, at the option of the contractor). This ensures that adequate attention to quality control is maintained, and parallels similar requirements in nuclear QA.

Other members of the contractor's quality control organization, besides the CQC representative, are the testing agency and various technical quality control representatives. Most testing relates to concrete strength and soil compaction, and is generally handled by a testing agency. Technical quality control representatives are usually

electrical and mechanical specialists, who assist the CQC representative in areas where he may have limited experience. These specialists are frequently subcontractor employees, but may be professional consultants at the contractor's option.

Management of quality control from the owner (Navy) standpoint more closely resembles highway construction than nuclear construction, largely due to the similarity in competitively bid contracts. The burden of risk in cost and time is born by the contractor; therefore, it is not necessary to organizationally separate inspection and surveillance from other aspects of contract administration.

Navy inspectors often discover that their duties in a CQC contract are not altogether different from those in a non-CQC job. The major differences are that the inspector no longer has the authority to control construction processes, and can no longer rely on the contractor to perform significant operations in his presence only. The first point is taken very seriously, and inspectors are instructed to refrain from recommending courses of action, especially in the case of nonconforming work. Their comments should be restricted to the acceptance of work in place or the identification of defects, under the philosophy that only the contractor can control the process. This concept is also paramount in highway and nuclear construction.

To be successful, Navy management of quality control must focus on the contractor's system. This starts with ensuring that the CQC plan is comprehensive and that his CQC personnel are well qualified. During construction, Navy management should ensure that the CQC plan is carried out completely and honestly. A deficiency discovered by a

government inspector should be reported to the CQC representative, not the superintendent. Navy recognition of the CQC system's importance goes a long way toward convincing the contractor of its importance. In this manner, the program is a cooperative venture, not just a shifting of responsibility.

Summary and Conclusions

The Navy Contractor Quality Control Program was instituted in 1970 for the purpose of redefining contractor and government roles in quality control. Although the major change involved the assignment of responsibility for quality to the contractor, the program is viewed as a joint contractor and Navy effort.

Contractor responsibilities include review and approval of shop drawings; inspection, testing, and approval of all construction; and documentation. Navy responsibilities include enforcement of the contract's CQC provisions, inspection of construction for acceptance, and surveillance of the contractor's quality control activities.

A major difference between Navy, highway, and nuclear quality systems is that the Navy program, while much less complex, is actually more comprehensive. Nuclear QA measures include only safety-related (Q-listed) work items, and highway SQC techniques apply only to specific materials, such as bituminous and Portland cement concrete. Navy CQC, on the other hand, applies to all items of construction (except those specifically delineated), and it is the dollar value of a Navy contract that determines whether or not CQC will be used. Because it is primarily management oriented, the nature of the project (building, airfield, pier, etc.) is not a factor in choosing CQC.

Despite CQC's comprehensiveness, there are aspects of highway and nuclear programs which are applicable to it. For example, the techniques of control charting and random sampling would be useful to the CQC representative in his inspection and testing of concrete or soil compaction. Although an independent agency does most of the testing, the CQC representative directs the activity. The use of statistical methods may not be appropriate for small concrete placements; but it would certainly be useful for a large concrete structure or an airfield in reducing the reliance on the CQC representative's intuitive judgment and eliminating bias in the sampling process. Control charts would be useful documentary evidence to demonstrate process control.

An aspect of nuclear QA applicable to CQC is the use of prewritten procedures for inspections. Navy specifications generally state what inspections are required; and if detailed procedures are involved, the applicable industry standards (e.g., ASTM or ACI) are referenced. Unfortunately, the referenced standards or codes are not always available at the jobsite, and the CQC representative relies on his experience and judgment in conducting the inspection. The results are not necessarily unsatisfactory, but the possibility of errors of omission exists. Nuclear programs circumvent the problem by requiring prewritten procedures and check lists for every conceivable inspection. Navy programs could be improved by requiring that the contractor include procedures and checklists for designated, critical inspections or tests in his CQC plan.

The strength of the CQC Program is its recognition of the following facts: only the contractor can control the quality of construction; the chief purpose of quality control is to prevent, rather than detect mistakes; and the role of the owner is instrumental in achieving success in quality control. It is no coincidence that highway and nuclear programs have recognized the same facts.

CHAPTER V

BUILDING CONSTRUCTION QUALITY CONTROL

Building construction is accomplished by both private and public owners. Private owners include individuals or organizations, such as corporations. Public owners include government agencies at federal, state, and local levels. Because Navy construction represents public contracting at the federal level, this chapter does not consider construction financed by the federal government. Despite their varied backgrounds, building owners share the same basic goals: to construct a building within a budget; to complete construction within a certain period of time; and to have the building meet their standards of quality. To achieve these goals, cost, schedule, and quality control techniques are employed.

The purpose of this chapter is to review the methods employed by owners to control quality in building construction from the points of view of planning, procedures, and organization and management. The controversy in recent years regarding the effectiveness of these methods, and the potential for its resolution through application of highway, nuclear, and Navy QC principles will also be discussed.

Background

Although there are currently many methods available to owners for controlling construction quality, this has not always been the case. Originally, the architect or "master builder" accomplished all design, engineering, and construction. As designs became more complex

and new construction materials and methods were developed, the architect could no longer handle both design and construction, and as a result, the general contractor evolved. At first, and for many years, there were only general contractors who employed craftsmen of all trades, and had a single contract with the owner.

As owners began to emphasize speed of construction, contractors responded by pooling their resources by craft, and subcontractor specialists evolved. In a similar manner, architects began to subcontract much of the design work to specialized engineering firms. As a result, the responsibilities for design and construction and inspection have been divided and subdivided.

Some owners continue to regard architects and general contractors as omnisicient in all aspects of design and construction, respectively. Schreiber (46) summarizes this point in an ASME technical paper:

> "The owner has been conditioned to believe that the general contractor knows all there is to know about construction, and the contractor wholly accepts the responsibility for the 'quality' inherent in his contract."

Other owners have adopted the opposite attitude. They feel that the general contractor, primarily concerned with making profits, has no regard for quality, and therefore must be constantly watched to ensure that the building is constructed properly.

The above owner attitudes represent extremes, but they, as well as more moderate approaches are, in fact, reflected in construction contracts. It is clear that owners have regard for quality control, but in building construction, it is the priority of this regard that is significant.

The building construction process begins with the owner, either a private organization or public agency, who decides he needs a building, hires an architect-engineer (A/E) to design it, and hires a contractor to construct it. During the design phase, the owner makes his requirements known. He defines the quality of structure he wants, when he needs it, and what it should cost. Often, he is informed that the desired quality cannot be met within the time and budgetary requirements, and more frequently than not, he finds it easier to sacrifice quality than accept a price increase or time delay.

During the construction phase, the emphasis on cost and time control becomes even more pronounced. Owners frequently insert "liquidated damages" or penalty clauses in their contracts to prevent time delays. Public agencies insist on competitively bid, fixed price contracts to ensure that costs remain within budget. Private owners insist on "guaranteed maximum" or "target" prices as insurance against excessive costs. The emergence of "construction management" as a profession charged with the responsibility of cost and schedule control is a clear signal of owners' regard for these two aspects of successful construction. In today's atmosphere of inflation and economic hardship, quality control has been relegated to a role of secondary importance.

The subordinate role of quality control is not limited to the viewpoint of owners. Contractors have long recognized the virtues of cost and schedule control. In fact, it is axiomatic in the industry that the best way to assure a profit is to "get in . . . and get out" as fast as possible. It is no wonder that supervisors and foremen are judged primarily on construction speed and dollar performance (actual

construction costs vs. estimated construction costs), and that quality is a secondary objective (49).

Although the quality objective is secondary, it is nevertheless important to owners that their buildings be safe and serviceable, and that they comply with the design requirements. To achieve these goals, owners have relied upon traditional quality control methods.

Planning

Quality control planning in building construction involves the preparation of plans and specifications. The A/E, with the owner's guidance, determines quality levels and specifies the materials and methods required to achieve the levels. He also references industry standards and codes, and frequently includes general conditions of a standard format.

The most common format for general conditions is AIA Document A201, "General Conditions of the Contract for Construction" (4). This set of conditions requires that the contractor perform all work in accordance with the plans and specifications, and calls for periodic site visits by the architect to verify proper performance. Quality control provisions, either as a contractor or architect requirement, are not provided.

Building specifications are usually classified as either "performance" or "prescriptive" types. Performance specifications describe the final product desired, leaving the choice of materials and methods up to the contractor. Prescriptive specifications stipulate the materials and techniques to be used in hopes that the final result will be satisfactory. Prescriptive specifications are equivalent to the "recipe" specifications described in highway construction; however,

building performance specifications are not statistically oriented as are highway specifications, and therefore are not equivalent to end result specifications.

A complete set of specifications is invariably neither of one nor the other type, but rather is a combination of the two. For example, a mechanical heating system design may have a performance specification which specifies the heating requirements, but leaves the choice of components and installation up to the contractor. A concrete specification, on the other hand, may be prescriptive in specifying the design mix, as well as how and under what conditions the concrete is to be placed. The type of specification used for a particular work item is significant to quality control, since it determines risk assumed by the A/E or contractor if the final quality is unsatisfactory. With a performance specification, the contractor assumes most of the risk, while with a prescriptive specification, the designer assumes most of the risk (48). In the latter case, the A/E may be more inclined to provide quality control inspection to ensure that the specified materials and methods are properly used, thus reducing the risk.

Whether a performance or prescriptive specification is used, the designer must set quality levels and determine requirements. The tendency in this function is to make the quality levels higher than necessary and the requirements more stringent than necessary as insurance that the final product will be satisfactory. The assumption is that the contractor will attempt to "get away with" the lowest acceptable quality, and the hope is that attained quality levels below specifications will still produce safe and serviceable buildings.

The traditional approach to quality planning has been criticized in the literature for producing unreasonable, unrealistic, and poorly worded specifications. Abdun-Nur (1) has listed a number of problems with specifications, three of which are summarized below:

1. Specification writing is largely a "cut and paste" operation assigned to subprofessionals, while the professionals concentrate on the drawings. The specification writers are not in tune with such matters as constructability or field procedures, and receive most of their guidance from previously used specifications not always applicable to the project at hand.
2. Specifications provide minimum quality levels which are rigidly enforced without regard to natural variability. Because variability is a law of nature, the absence of reasonable tolerances produces unrealistic specifications.
3. Specifications are written in such a manner that the designer "remains in the driver's seat" where he can retain control, but cannot physically do the contractor's work. This creates legal problems for the contractor who has the responsibility but not the control.

It should be noted that the Construction Specifications Institute has devoted considerable effort toward eliminating the problem of poorly worded specifications. The issues of whether to use minimum quality levels or target quality levels (with tolerances), and whether to

assign quality control inspection to the contractor or resident engineer have, however, not been addressed.

With a good contractor, a resonable A/E, a just owner, and a good working relationship between the three, specificaion problems can be reduced, but with or without these conditions, poorly written specifications add significantly to the difficulty of the quality control effort.

It should be pointed out that poorly written specifications have also been a problem in highway, nuclear, and Navy contracts. The highway industry has taken specific steps to correct the problem by adopting statistical end result specifications. In addition, highway departments maintain a continuous assurance testing program to modify specifications as the need arises. The problem has been alleviated to a great degree in nuclear construction due to contractor participation in QA planning before the specifications are written. The problem still exists in Navy construction, although the fact that the CQC concept has effectively taken the designer "out of the driver's seat" has improved the situation considerably.

Abdun-Nur (1) has suggested that the solution lies in increased A/E attention to specification writing, and a probability approach to choosing acceptance criteria. It is the writer's conclusion that these plus contractor input at the predesign stage (whenever possible) would result in the realistic and reasonable specifications, which are the foundation of an effective quality control system.

Procedures

Construction textbooks are uniform in reference to quality control procedures as "field inspection" procedures, which are the responsibility of a resident engineer or architect (14, 20, 44). The use of a resident engineer implies that a representative of the A/E (private work) or the owner (public work) will be assigned to the job site on a full-time basis. Retention of the architect usually provides for periodic inspections, the frequency of which are negotiated with the owner.

The resident engineer or inspector conducts field inspections on a continuous basis "to maintain vigilant checks for any and all defects in the completed work (20)." Field inspection procedures prohibit interference with the contractor's operations, "unless it is to prevent something from being done incorrectly (14)."

Architect field inspection procedures involve periodic jobsite visits to assure contractor compliance with the plans and specifications. Included are the responsibility to reject all nonconforming work and the authority to stop work if necessary (44).

There is no uniform set of procedures for building construction field inspection or quality control. Contracts between owners and A/E's may specify the frequency of inspections (periodic or continuous), but they do not tell the inspector how to inspect or what to inspect. These matters are left to the discretion of the inspector, and although he may be guided by industry inspection codes and standards, it is essentially his own judgment and experience which dictate his procedures.

The above procedures work quite well with a competent contractor, a qualified inspector, and a good working relationship between the two. The architect's or resident engineer's presence reduces owner anxieties over project quality, and contractors appreciate the assistance in discovering errors and the readily available interpretations of plans and specifications.

The greatest criticism of the procedures has been that inspectors lack experience and qualifications (19, 22, 36, 47, 49). A good inspector can prevent major construction failures or identify deficiencies whose early correction can prevent costly and time consuming rework. An unqualified inspector can "wreak havoc" on a construction site, causing unnecessary time delays and adding significantly to contractor and owner costs. The practices of inexperienced or overzealous inspectors have been estimated to add as much as $500,000,000 annually to the cost of all construction nationally (43).

A survey in 1972 traced inspector problems to insufficient pay, lack of formal training, lack of a certification program, improper supervision, insufficient authority, and inexperience. It is clear that each of these problems could be corrected if owners were willing to pay more money for inspection services. Unfortunately, owners are too often preoccupied with cutting costs, and hence, the architect-engineer is unable to include sufficient inspection money in his fee.

Inspector problems have also existed in highway, nuclear, and Navy construction, but the introduction of quality control systems has reduced the problem considerably. In nuclear QA, the solution has been the enforcement of minimum standards and the inclusion of

certification requirements. In highway and Navy construction, no direct steps have been taken to increase inspector competency, but the shift in QC responsibilities to the contractors has reduced their reliance on the inspectors.

It is the writer's conclusion that training and certification programs are needed for building construction inspectors. Building owners who bear the costs of inspection should realize this need and insist on minimum inspector standards for specific projects. This is essentially the approach of nuclear QA programs which have been successful in this regard.

Organization and Management

Formal quality control programs, such as highway, nuclear, and Navy programs, do not exist in building construction; nevertheless, a management effort on the part of owners and contractors is required in order to ensure that the plans and specifications are properly executed. The motivation for this management effort is basic: the owner is unwilling to pay for a defective building, therefore, he must assure himself that the quality is satisfactory; the contractor wants to get paid, therefore, he must ensure that a satisfactory quality building is presented to the owner.

As a rule, building contractors do not provide for quality control as a separate function in their project or home office organizations. The project manager and superintendent for a particular job, are assigned the responsibilities for all aspects (cost, schedule, and quality) of project control. As mentioned earlier, contractor personnel are most often judged on their ability

to build a project on time and within budget. Their ability to achieve quality, although a secondary objective, is taken for granted only in the less reputable contractor organizations.

Reputable contractors take pride in their work, and hire highly competent supervisors. They value their good reputation and are willing to sacrifice profits rather than produce a building of poor or marginal quality. They often cite high quality as one of their chief organizational objectives; yet they have no formal or standing quality control program. They frequently prepare project manuals which provide field personnel with job control procedures, such as timekeeping and administration of subcontracts, but do not include quality control procedures. Quality is achieved through the skill, judgment, and experience of the project superintendent with the support of the project manager. This skill is invariably dedicated toward the prevention of costly errors or defects. In this way, their quality efforts contribute to company profits and avoid time delays.

An alternative contractor approach to quality is to rely on the judgment and expertise of the inspector or resident engineer to control the quality. Under this approach, the inspector is not in a position to control preparations for construction because selection of construction techniques is clearly up to the contractor. As a result, he is forced into a role of detecting errors after they result in defective work. In many cases, it is impossible or inconvenient to remove and replace nonconforming work and, as a result, the overall quality of the building suffers. To avoid this situation, many private owners negotiate contracts with reputable contractors, rather than risk getting a marginal contractor in a competitive bid.

To summarize, contractor quality control in building construction is not a well-managed, highly organized effort, regardless of the company's reputation. It is, rather, a company objective which is taken more seriously by some organizations than others.

Owner management of quality control is a process of assigning the responsibility for inspection to the architect-engineer or to the owner's own forces, and following up on the process to see that it is accomplished to his satisfaction. It is the issue of assignment of inspection and quality control responsibilities to the A/E or contractor which has created the most controversy in construction quality control. Clearly, the vast majority of buildings are constructed in the traditional manner with the A/E or owner responsible for inspection. Proponents of this method believe the designer to be more qualified than the contractor and more mindful of the owner's needs and desires.

There are difficulties with owner or A/E inspection, however, which have been experienced in highway and Navy construction, as well as building construction. These include contractor overreliance on the inspector to make construction decisions, and construction delays due to waiting for inspector approvals. The most serious problem relates to whether or not the A/E, responsible for inspection, is also responsible for the building's final quality. If the architect's inspector fails to detect a deficiency during construction, but discovers it during the final inspection, the contractor may successfully claim that the earlier nondiscovery constituted tacit approval. If the inspector detects a nonconformance during construction, recommends a solution, and the final result is unsatisfactory, the A/E may also be held responsible. Court cases have held the A/E and

contractor jointly liable for construction failures due to contractor negligence, which the A/E should have detected (48). A/E or owner responsibility for quality control inspection is a problem because the inspector is in a position of responsibility for quality without the requisite control over the construction process. Only the contractor can effectively control the process.

The above difficulties have been eliminated in highway, nuclear, and Navy construction by recognizing that it is logical and proper to assign the responsibility for quality control inspection and testing to the contractor. Critics of this concept fail to realize that the power of acceptance, which includes acceptance inspection and testing, is retained by the owner.

Summary and Conclusions

Building construction quality control is largely a secondary objective of owners and contractors due to the economic pressure of time and cost control. The basic activities include the preparation of specifications, the assignment of responsibility for field inspection, and the accomplishment of inspection and testing. Inspection procedures are informal, and conducted by representatives of the owner or A/E. The contractor is not assigned any specific quality control duties, although contract provisions state that he is responsible for performing in accordance with the plans and specifications.

A number of problems related to quality control have been identified in the literature, the more serious of which are poorly written specifications, underqualified inspectors, and improper

assignment of responsibility for inspection. The problems have led to increased costs, legal disputes, and a general emphasis on detecting errors after they occur, rather than preventing them from occurring.

It is the writer's conclusion that when the above problems are present, the underlying causes are insufficient planning, lack of effective procedures, and the absence of a management commitment to quality control. It is a further conclusion that the problems could be effectively eliminated through techniques already demonstrated in highway, nuclear, and Navy quality control systems.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The attainment of quality has always been an objective of the construction industry; however, until recent years, the quality control aspects of planning and management have not been emphasized. In the early 1970's, the industry was introduced to quality control systems which recognized that, to be effective, quality control must be an active, conscious effort during all phases of a project. Considered in this thesis were three systems: highway construction statistical quality control (SQC); nuclear power plant construction quality assurance (QA); and U. S. Navy construction contractor quality control (CQC). A comparative analysis was drawn between these systems and building construction quality control which represents the traditional approach.

The purpose of the analysis was to provide, in a single document, an overview of management tools available in construction quality control. To provide a common basis for comparison, each approach was analyzed interms of planning, procedures, and organization and management.

Summary

Each of the four quality control programs requires planning, procedures, and organization and management. Planning consists of quality related activities which precede the commencement of construction activities; procedures include activities that occur during construction; and organization and management represent the techniques

employed by owners and contractors to ensure that procedures are carried out smoothly and efficiently.

Planning

From the owner point of view, quality control planning involves the establishment of quality levels and requirements in the project specifications. From the contractor viewpoint, it involves preparation of procedures to implement quality control. In highway construction, the state highway agencies (owners) are becoming increasingly involved with applying the principles of statistical quality control to the setting of quality level tolerances and the development of sampling and acceptance plans. The result is a "statistical end result specification." Contractor preparation of a formal quality control plan is usually optional.

Nuclear QA planning is likely to be a joint utility (owner) and contractor effort which results in a formal, written QA Program. The program's purpose is to demonstrate the utility's plans to comply with Nuclear Regulatory Commission (NRC) requirements. Upon acceptance by the NRC, it is incorporated into the project specifications.

Navy CQC planning is primarily concerned with determining which work items are to be inspected by the contractor and which by the government. The contractor must prepare a written CQC plan which is a comprehensive description of his shop drawing review, inspection, testing, and documentation procedures.

Building construction planning involves a decision as to who (A/E, owner, resident engineer) will provide inspection services and at what frequency.

Procedures

Quality control procedures involve activities of the contractor, owner, and sometimes the A/E. Highway SQC procedures involve process control sampling and testing by the contractor and acceptance sampling and testing by the owner. Some states also conduct assurance sampling and testing to evaluate the effectiveness of specifications.

Nuclear procedures involve parallel activities at several levels. Detailed construction procedures constitute the first level of control with the emphasis on "doing it right the first time." Quality Control (QC), also performed by the contractor, is the first level of approval and inspection. Quality Assurance (QA), performed by the contractor or architect-engineer (A/E), and the utility, is a check on the performance of QC and construction. NRC inspections and audits are a further check to ensure that QA is performed properly.

Navy contractor procedures include review and approval of shop drawings; inspection, testing, and approval of work in place; and documentation. Government activities involve enforcement of CQC provisions (contract administration), surveillance of CQC activities, and acceptance inspection of work in place.

Building construction procedures are largely limited to the inspection and testing activities of the resident engineer or the architect. Individual contractors have their own methods of ensuring compliance with the plans and specifications, but the procedures are undefined and conducted at the discretion of the project manager and superintendent.

Organization and Management

In any quality control system, it is essential that the activities be properly organized and managed. In highway, nuclear, and Navy systems, the organizational emphasis is on the assignment of process control and quality control responsibilities to the contractor, and the retention of acceptance inspection and surveillance tasks by the owner. Nuclear and Navy contracts contain specific management requirements, such as the provisions for authority and organizational freedom of QC and QA personnel, while highway specifications contain very little management guidance.

Building construction contractors do not, as a rule, have separate quality control departments within their organizations, nor do their project management manuals contain quality control procedures. Management attention to QC is dictated by whether or not high quality construction is perceived by top management to be a prime company objective.

Conclusions

From the comparative analysis of highway, nuclear, and Navy quality control systems, and building construction quality control, the following conclusions can be drawn:

1. Assuming that construction of high quality is desirable to owners, the "quality control system" holds the greatest promise for achievement of that goal. A quality control system is superior to traditional quality control, which relies mostly on owner or A/E inspection, because it is an active effort over all phases (predesign, design,

construction) of a project, and because its activities require the involvement of all participating organizations (owner, contractor, A/E).

2. Implementation of a QC system requires an owner commitment prior to selection of an A/E or contractor. The owner cannot assume that these organizations will automatically perform QC functions, because each is under pressure to reduce costs and construction time. The owner should ensure that they actively participate in the QC effort by including specific contract requirements to that effect.

3. It is not sufficient that the owner rely on contract provisions to achieve well-managed quality control. He should, in addition, monitor and, if necessary, audit both construction and quality control to ensure that they are accomplished in accordance with the contract requirements.

4. The owner should insist that the contractor be responsible for both process control and quality control, and that the contractor's efforts in either case be focused on preventing errors rather than detecting them after they occur. To further emphasize the importance of preparation for construction, the contractor should be required to review and approve shop drawings prior to submission to the A/E or owner for final approval.

5. The contractor should be required to develop a quality control plan which describes his inspection, testing, documentation and management procedures. The plan is a contractor's statement of intent to perform the required construction and quality control tasks properly, therefore, the plan should be approved by the owner prior to jobsite mobilization.
6. Within his organization, the contractor should maintain a quality control group. To insulate this group from the pressures of cost and schedule, its duties should be limited to quality control. In addition, it should have the necessary authority and organizational freedom to effectively perform its responsibilities.
7. The contractor should keep accurate and comprehensive records of all tests and inspections. His ability to demonstrate through his records that a process (e.g., concrete production) was "in control" may lead to a conclusion that the specifications rather than the construction were defective.
8. The project A/E should be committed to writing clear and realistic specifications. To be realistic, quality levels should include tolerances based on the natural variability of the process being considered. Whenever possible, to eliminate bias

and promote fairness to both the contractor and owner, random sampling, in lieu of representative sampling, should be used.

9. The A/E should include in the specifications, a list of minimum required tests and inspections to be conducted by the contractor. He should also include a description of the acceptance criteria for each work item, and a list of inspections and tests to be conducted by the owner. It is essential in a quality control system that each participating organization understand in advance exactly what the responsibilities and activities of all concerned will be.

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